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(54) Plasma reactor using UHF/VHF resonant antenna source, and processes.

(57) A plasma reactor (10) uses a ring antenna (25) driven by RF energy (HF, VHF, or UHF) and produces a circularly polarized electromagnetic wave inside the ring. Inside the ring, this wave has a transverse circular electric field and a longitudinal magnetic field. A static magnetic field may be used with the E/M field (typically with direction perpendicular to the wave's electric field component). Placed adjacent to a dielectric window, dome, or bell jar (17), the above apparatus generates a high density, low energy plasma inside a vacuum chamber for etching metals, dielectrics and semiconductor materials (5). When operated at resonance (antenna (25) tuned to resonance with excitation frequency, and magnetic field tuned to resonance with excitation frequency), plasma density may be maximized. Auxiliary bias energy applied to the wafer support cathode (32C) controls the cathode sheath voltage and controls the ion energy independent of density. Various etch processes, deposition processes and combined etch/deposition processes (for example, sputter/facet deposition) are disclosed. Processing of sensitive devices without damage and without microloading can thus be achieved providing high yields.

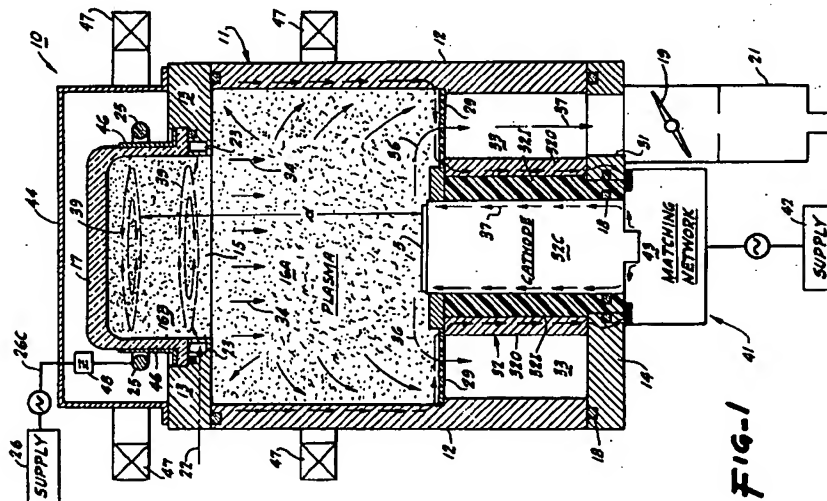


FIG-1

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The present invention relates to a process for forming or generating a plasma, a plasma processing system and to an RF plasma processing reactor.

The trend toward increasingly dense integrated geometries has resulted in components and devices of very small geometry which are electrically sensitive and susceptible to damage when subjected to wafer sheath voltages as small as approximately 200-300 volts due to energetic particle bombardment or radiation. Unfortunately, such voltages are of smaller magnitude than the voltages to which the circuit components are subjected during standard integrated circuit fabrication processes.

Structures such as MOS capacitors and transistors fabricated for advanced devices have very thin (thickness < 200 Angstroms) gate oxides. These devices may be damaged by charge-up, resulting in gate breakdown. This can occur in a plasma process when neutralization of surface charge does not occur, by non-uniform plasma potential/or density, or by large RF displacement currents. Conductors such as interconnect lines may be damaged for similar reasons as well.

RF Systems

Consider first prior art semiconductor processing systems such as CVD (chemical vapor deposition) and RIE (reactive ion etching) reactor systems. These systems may use radio frequency energy at low frequencies from about 10-500 KHz up to higher frequencies of about 13.56 - 40.68 Mhz. Below about 1 Mhz, ions and electrons can be accelerated by the oscillating electric field, and by any steady state electric field developed in the plasma. At such relatively low frequencies, the electrode sheath voltage produced at the wafers typically is up to one or more kilovolts peak, which is much higher than the damage threshold of 200-300 volts. Above several Mhz, electrons are still able to follow the changing electric field. More massive ions are not able to follow the changing field, but are accelerated by steady state electric fields. In this frequency range (and at practical gas pressures and power levels), steady state sheath voltages are in the range of several hundred volts to 1,000 volts or more.

Magnetic Field-Enhancement

A favorite approach for decreasing the bias voltage in RF systems involves applying a magnetic field to the plasma. This B field confines the electrons to the region near the surface of the wafer and increases the ion flux density and ion current and, thus, reduces the voltage and ion energy requirements. By way of comparison, an exemplary non-magnetic RIE process for etching silicon dioxide might use RF energy applied at 13.56 Mhz, an asymmetrical system of 10-15 liters volume, 50 millitorr pressure and an anode area to wafer-support cathode area ratio of approximately (8-10) to 1, and develop wafer (cathode) sheath voltage of approximately 800 volts. The application of a magnetic field of 60 gauss may decrease the bias voltage approximately 25-30 percent, from 800 volts to about 500-600 volts, while increasing the etch rate by as much as about 50 percent.

However, the application of a stationary B field parallel to the wafer develops an $E \times B$ ion/electron drift and an associated plasma density gradient which is directed diametrically across the wafer. The plasma gradient causes non-uniform etching, deposition and other film properties across the wafer. The non-uniformities may be decreased by rotating the magnetic field around the wafer, typically either by mechanical movement of permanent magnets, or by using pairs of electromagnetic coils which are driven in quadrature, 90 degrees out of phase, or by instantaneously controlling the current in pairs of coils to step or otherwise move the magnetic field at a controlled rate. However, although rotating the field reduces the non-uniformity gradient, typically some degree of non-uniformity remains.

Furthermore, it is difficult to pack coils and, in particular, to pack two or more pairs of coils about a chamber and to achieve a compact system, especially when using a Helmholtz coil configuration and/or a multi-chamber system of individual magnetic-enhanced reactor chambers surrounding a common loadlock.

A unique reactor system which has the capability to instantaneously and selectively alter the magnetic field strength and direction, and which is designed for use in compact multi-chamber reactor systems, is disclosed in commonly assigned U.S. Patent 4,842,683, issued June 27, 1989, in the name of inventors Cheng et al.

* 1 Angstrom = 0.1 nm

* 1 millitorr = 1.3×10^{-4} bar

Microwave/ECR Systems

Microwave and microwave ECR (electroncyclotron resonance) systems use microwave energy of frequencies >800 MHz and, typically, frequencies of 2.45 GHz to excite the plasma. This technique produces a high density plasma, but low particle energies which may be below the minimum reaction threshold energy for many processes, such as the reactive ion etching of silicon dioxide. To compensate, energy-enhancing low frequency electrical power is coupled to the wafer support electrode and through the wafer to the plasma. Thus, the probability of wafer damage is decreased relative to previous systems.

Microwave and microwave ECR systems operated at practical power levels for semiconductor wafer processing such as etch or CVD require large waveguide for power transmission, and expensive tuners, directional couplers, circulators, and dummy loads for operation. Additionally, to satisfy the ECR condition for microwave ECR systems operated at the commercially available 2.45 GHz, a magnetic field of 875 gauss is necessitated, requiring large electromagnets, large power and cooling requirements.

Microwave and microwave ECR systems are not readily scalable. Hardware is available for 2.45 GHz, because this frequency is used for microwave ovens. 915 MHz systems are also available, although at higher cost. Hardware is not readily or economically available for other frequencies. As a consequence, to scale a 5-6 in. microwave system upward to accommodate larger semiconductor wafers requires the use of higher modes of operation. This scaling at a fixed frequency by operating at higher modes requires very tight process control to avoid so-called mode flipping to higher or lower order loads and resulting process changes. Alternatively, scaling can be accomplished, for example, for a 5-6 in. microwave cavity, by using a diverging magnetic field to spread out the plasma flux over a larger area. This method reduces effective power density and thus plasma density.

HF Transmission Line System

Commonly assigned European patent application 91112917.9 is incorporated by reference. This incorporated application discloses a high frequency VHF/UHF reactor system in which the reactor chamber itself is configured in part as a transmission line structure for applying high frequency plasma generating energy to the chamber from a matching network. The unique integral transmission line structure permits satisfaction of the requirements of a very short transmission line between the matching network and the load and permits the use of relatively high frequencies, 50 to 800 MHz. It enables the efficient, controllable application of RF plasma generating energy to the plasma electrodes for generating commercially acceptable etch and deposition rates at relatively low ion energies and low sheath voltages. The relatively low voltages reduce the probability of damage to electrically sensitive small geometry semiconductor devices. The VHF/UHF system avoids various other prior art shortcomings, such as the above-described scalability and power limitations.

In view of the above discussion, it is one object of the present invention to provide an improved process for forming or generating a plasma, an improved plasma processing reactor and an improved RF plasma processing system. These objects are solved by the process for forming a plasma of independent claim 1 by the process for generating a plasma of independent claims 2, the plasma processing reactor of independent claim 95 and the RF plasma processing system of independent claim 70. Further advantageous features, aspects and details of the invention are evident from the dependent claims, the description, examples and drawings. The claims are intended to be understood as a first non-limiting approach of defining the invention in general terms.

The invention provides an inventive plasma reactor which uses a high frequency (HF) energy source and a resonant substantially closed loop antenna for coupling the associated HF electromagnetic wave to the plasma.

The invention according to one aspect provides a plasma reactor and process which use high frequency AC energy to generate the plasma.

In another aspect of the present invention a plasma reactor and process are provided which use VHF/UHF energy to generate the plasma.

In another, related aspect the invention provides a plasma reactor system and process which couple elliptically (including circularly) polarized VHF/UHF energy into the vacuum chamber to generate the plasma.

In yet another, related aspect the invention provides a plasma reactor system and process which couple circularly polarized VHF/UHF energy into the vacuum chamber to generate the plasma.

* 1 inch = 2.54 cm

In yet another aspect, the invention provides a plasma reactor system which couples circularly polarized VHF/UHF energy to generate a plasma and to define its plasma density and ion current density, and an auxiliary bias applied to a cathode (wafer electrode) to define sheath voltage and thus ion energy of said cathode sheath.

5 In still another aspect the invention provides a reactor and numerous associated embodiments of a process which satisfy the above objectives and rectify shortcomings of the prior art.

In one specific aspect, the present invention which satisfies the above and other objectives is embodied in the construction and operation of an RF plasma processing system comprising a plasma processing chamber and means for coupling high frequency elliptically polarized electromagnetic energy into the
10 processing chamber for generating a plasma within the chamber for fabricating an article such as a semiconductor wafer positioned, for example, at the coupling means or downstream relative to the coupling means.

Preferably, high frequency power is used which is within the range 50-800 MHz. Preferably, the coupling means is a single turn, substantially closed loop resonant antenna.

15 In another aspect, the system includes a dielectric dome which defines a chamber therein and a substantially closed loop antenna for coupling the high frequency electromagnetic energy into the chamber. The article which is fabricated can be located within the dome, within or closely adjacent the plane of the antenna, or preferably, downstream of the antenna.

Other preferred aspects may include a conductive shield which is interposed between the single turn
20 antenna or other coupling means and the chamber to prevent coupling of the electric field component of the high frequency electromagnetic energy into the chamber. Also, a high frequency reflector positioned surrounding the single turn antenna or other coupling means concentrates radiation of the high frequency energy into the chamber. An AC power supply and control system couples AC power, typically of lower frequency than the antenna power, to a wafer support cathode, thereby effecting control of the cathode
25 sheath voltage and ion energy, independent of the plasma density control effected by the high frequency power.

Magnetic enhancement may be supplied by peripheral permanent or electromagnet arrangements which apply a controlled static magnetic field orthogonal to the plane of the antenna, selected from uniform, diverging and magnetic mirror configurations, for controlling the location of and the transport of the plasma
30 downstream relative to the wafer. Also, magnets may be mounted around the chamber for applying a multipolar cusp field to the chamber in the vicinity of the wafer for confining the plasma to the wafer region while substantially eliminating the magnetic field across the wafer. In addition, a magnetic shunt may be positioned surrounding the wafer and the wafer support electrode for diverting any magnetic field from the wafer support electrode.

35 In another aspect, the physical length the antenna approximates $n\lambda/4$, where n preferably is a small odd or even integer and λ is the wavelength of the electromagnetic excitation frequency. Preferably, the length is selected for low mode operation, e.g., $n = 2$, the mode being $\lambda/2$.

The system construction permits scaling of its size by selecting the frequency of operation, while retaining low mode operation.

40 Other apparatus aspects, not exhaustive, include matching the impedance of the antenna to the high frequency source via coupling means selected from inductive, capacitive, and conductive impedances. Also, means may be provided for tuning the antenna to resonance, selected from fixed, distributive, inductive and capacitive impedances. In a presently preferred embodiment, variable capacitors are incorporated in or connected to the antenna for matching the impedance of the antenna to that of high frequency source and
45 for tuning the antenna to resonance.

In another aspect, the invention is embodied in the construction and operation of a plasma processing reactor, comprising: a housing including a dielectric dome defining a plasma chamber therein; electrode means within the plasma chamber for supporting a semiconductor wafer; a gas inlet manifold in the housing for supplying reactant gas to the plasma chamber; vacuum pumping means communicating with the plasma
50 chamber for maintaining a vacuum therein; and a high frequency energy source comprising a substantially closed loop antenna surrounding the dome and a conductive shield interposed between the antenna and the dome for cooperatively shunting the direct electric field component of the high frequency electromagnetic energy from the plasma chamber and coupling the magnetic component of the high frequency electromagnetic energy into the plasma chamber for inducing closed loop electric fields therein.

55 In other, process aspects, the invention is embodied in a process for coupling high frequency elliptically polarized electromagnetic energy into a processing chamber for generating a plasma within the chamber for effecting fabrication of materials selected from etching of materials, deposition of materials, simultaneous etching and deposition of materials and/or sequential etching and deposition of materials.

In another aspect, the process according to the invention comprises supporting an object on an electrode within a vacuum chamber; supplying gas to the vacuum chamber; using a substantially closed loop antenna adjacent to the chamber, generating high frequency electromagnetic energy; and coupling the electromagnetic energy into the chamber thereby generating a plasma for fabricating one or more materials on the object.

The process according to the invention also comprises supporting an object within a vacuum chamber; supplying gas to the vacuum chamber; using a substantially closed loop antenna adjacent the chamber, generating high frequency electromagnetic energy; and coupling the magnetic component of the electromagnetic energy into the chamber for inducing closed loop electric fields therein, thereby generating a plasma from the gas for fabricating one or more materials on the object. In yet another aspect, the object is supported on an electrode and AC power is applied to the electrode for independently controlling the cathode sheath voltage and the ion energy, with respect to plasma density and ion flux density.

Specific process aspects include but are not limited to etching oxide, including etching contact holes in oxide formed over polysilicon (polycrystalline silicon) and etching via holes in oxide formed over aluminum; so-called "light" etching of silicon oxide and polysilicon; high rate isotropic and anisotropic oxide etching; etching polysilicon conductors such as gates; photoresist stripping; anisotropic etching of single crystal silicon; anisotropic photoresist etching; low pressure plasma deposition of nitride and oxynitride; high pressure isotropic conformal deposition of oxide, oxynitride and nitride; etching metals, such as aluminum and titanium, and compounds and alloys thereof; and sputter facet deposition, locally and globally, and with planarization.

Brief Description of the Drawing

The above and other aspects of the invention are described with respect to the drawing in which:

FIG. 1 schematically depicts an RF reactor system in accordance with the present invention;

FIG. 2 schematically depicts a preferred antenna arrangement;

FIG. 3 depicts the spatial relationships between the ground shield and the antenna and other components;

FIGS. 4A-4D depict various magnetic enhancement fields;

FIG. 5 is a block diagram of a presently preferred power control system;

FIG. 6 depicts a representative integrated circuit via hole; and

FIG. 7 depicts the via hole of FIG. 6 after application of a widening sequence in accordance with my invention.

Detailed Description of the Preferred Embodiment(s)

1. OVERVIEW

FIG. 1 is a schematic sectional view of a plasma reactor chamber system 10 which uses a circularly polarized plasma source arrangement, a magnetically-enhanced plasma source arrangement and other aspects of the present invention. The exemplary chamber is a modification of that depicted in the above mentioned European patent application, which includes an integral transmission line structure. The salient features of my invention are applicable generally to plasma reactor chambers. Furthermore, it will be understood by those of skill in the art and from the description below that various features of the invention which cooperatively enhance the performance of the reactor system may be used separately or may be selectively omitted from the system. For example, the process conditions provided by the circularly polarized plasma source arrangement frequently eliminate any need for magnetic enhancement.

The exemplary system 10 includes a vacuum chamber housing 11, formed of anodized aluminum or other suitable material, having sidewalls 12 and top and bottom walls 13 and 14. Anodized aluminum is preferred because it suppresses arcing and sputtering. However, other materials such as bare aluminum and process-compatible polymers or quartz or ceramic liners can be used. The chamber can be heated or cooled for process performance. Top wall 13 has a central opening 15 between a lower chamber section 16A defined between walls 12-12 and an upper chamber section 16B defined by a dielectric dome 17. The dome preferably is quartz but can be made of several dielectric materials, including alumina and alpha-alumina (sapphire). The dome may be heated or cooled as required for process performance. A fluid or gas heat transfer medium may be used, or heating elements may be used to heat the dome directly. Various vacuum seals 18 such as O-rings are interposed between the various mating surfaces to maintain vacuum-tight enclosure. The interior of the chamber housing 11 (chamber 16) is evacuated via a throttle valve 19

(which regulates pressure independent of flow rate) in a vacuum line 21 which connects to a vacuum pumping system (not shown).

Reactant gases are supplied to the chamber 11, as indicated schematically at 22, typically from one or more sources of pressurized gas via a computer-controlled flow controller (not shown) and enter the internal vacuum processing chamber 16 through ring gas manifold 23, which is mounted on the inside of or integral with, top wall 13. The manifold 23 preferably supplies etching gas and/or deposition gas at a slight upward angle to the chambers/chamber sections 16B and 16A for developing an etching and/or deposition plasma upon application of high frequency RF energy. Gases may be brought into the process chamber instead of through the manifold, or in addition to through the manifold. For example, it may be desired to bring an inert gas or other gas into the manifold 23, and bring other reactant gases in via a lower manifold or gas inlet (not shown) in the process chamber below. The high frequency (HF) energy such as, preferably, VHF/UHF energy of frequency 50 to 800 MHz is applied by a substantially closed loop antenna 25 powered by a high frequency (HF) source 26, and effects plasma excitation in the chamber 16 by Faraday's Law of induction coupling. This contrasts with conventional RF system arrangements, in which the RF power is applied between two electrodes, typically the wafer support electrode 32C, the upper surface of which supports wafer 5, and a second electrode which is the sidewalls 12, top wall 13 and/or manifold 23 of the reactor chamber.

Preferably, the gas flow from the upper chamber section 16B is downward toward the wafer 5 and is then pumped radially outward from the wafer. To this end, an annular vacuum manifold 33 is defined about cathode transmission line structure 32, between chamber wall 12 on one side and the outer transmission line conductor 320 on the other, and between the chamber bottom wall 14 on the bottom and a conductive pumping screen 29 on the top. The manifold screen 29 is interposed between the vacuum manifold 33 and the plasma chamber 16A and provides a conductive electrical path between chamber walls 12 and the outer conductor 320 of the transmission line structure 32. The manifold 33 defines an annular pumping channel for implementing uniform radial pumping of exhaust gases from the periphery of wafer 5. The exhaust manifold 33 communicates into the exhaust gas system line 21 via one or more apertures 31 in the bottom wall 14. The overall gas flow is along path 22 into the inlet manifold 23, then along path 34 from the upper chamber section 16B toward wafer 5, along path 36 radially outwardly from the peripheral edge of the wafer and through screen 29 into the gas outlet manifold 33, and along path 37 from the exhaust manifold 33 to the exhaust system 21.

The ring antenna 25 is positioned adjacent the dome 17 and the plasma chamber 16B for coupling the relatively high frequency (HF) electromagnetic (em) energy into the chamber. By Faraday's Law of induction coupling, the changing B (magnetic) component of the em energy induces closed loop AC electrical fields and resulting currents 39-39 which energize the process gas and thus form a plasma in chamber 16 (numeral 16 collectively designates the chamber 16A and 16B and the plasma) characterized by relatively high density and low energy ions. The plasma is generated in the plane of the dome concentrated in the plane of the antenna and active species including ions, electrons, free radicals and excited neutrals move downstream toward the wafer by diffusion and by bulk flow due to the prevailing gas flow described herein. Also, an appropriate magnetic field can be used to extract ions and electrons toward the wafer as described below. Optionally, but preferably, a bias energy input arrangement 41 comprising a source 42 and a bias matching network 43 couples relatively low frequency (LF) energy to the wafer support electrode 32C for selectively increasing the plasma sheath voltage at the wafer and thus selectively increasing the ion energy at the wafer.

A reflector 44 which essentially is an open-bottom box encloses the antenna at the top and sides but not at the bottom. The reflector prevents radiation of the HF energy into free space and thereby concentrates the radiation and dissipation of the power in the plasma to enhance efficiency.

Preferably, an open-ended Faraday shield 46, described in greater detail below, is positioned just inside, above and below the ring antenna 25 to permit the magnetic field coupling to the plasma but preclude direct electric field coupling, which could induce gradients or non-uniformities in the plasma, or accelerate charged particles to high energies.

As described in greater detail below, optionally, one or more electromagnets 47-47 or permanent magnets are mounted adjacent the chamber enclosure 11 for providing a static shaped-magnetic field for enhancing the density of the plasma at the wafer 5.

In short, the invention uses the magnetic component of elliptically (elliptically includes circularly) polarized relatively high frequency electromagnetic energy, typically 50 MHz to 800 MHz (high frequency relative to the optional bias energy but typically much lower than microwave or microwave-ecr frequencies), to induce circular electric fields inside a vacuum chamber for generating a plasma characterized by high density and relatively low energy, without coupling the non-uniformity-inducing HF direct electric field

component into the chamber and without coupling potentially damaging HF energy through the wafer 5. In the preferred, illustrated downstream plasma source arrangement, the e/m wave is fully absorbed remote from the wafer, with high plasma density, ensuring that the wave does not propagate to the wafer and thus minimizing the probability of damage. Selectively, and optionally, relatively low frequency (LF) auxiliary AC bias energy is applied to the wafer support electrode 32C for increasing the wafer sheath voltage and, thus, the ion energy as required.

2. ANTENNA

Ring antenna 25 is preferably circular but could be any resonant, preferably single turn configuration including circular and polygonal configurations. The single turn configuration is preferred because its small vertical size (a small volume of plasma is excited) and its inducing circular electric fields in a plane substantially parallel to the plane of the wafer avoiding potentially damaging axial component of induced E field, but a multiple turn spiral arrangement (preferably of only a few turns to minimize size (volume excited) could be used. Also, a stack of multiple single-turn antennas could be used to expand the plasma volume. A resonant length (the circumferential length) is chosen which is substantially either an even multiple of quarter wavelengths of the excitation or resonant frequency λ ($n = \lambda/4$ wherein $n = 2, 4, 6$, etc.) or an odd multiple of quarter wavelengths of λ ($n = 1, 3, 5$, etc.). Preferably, to prevent process changes due to mode flipping to lower or higher modes of operation, low mode operation is selected ($n =$ small integer, preferably 1, or most preferably 2).

The ends of the antenna are referenced to ground either by an open circuit, a short circuit connection or inductive or capacitive connection to ground. For example, both ends may be directly grounded or one may be grounded and the other open. The presently preferred construction comprises half wavelength periodicity ($n \lambda/4$, $n = 2$) with both ends grounded such that the voltage peak varies from zero at the ends to a maximum at the middle. This lowest order, half wavelength mode of operation provides reliable operation free from mode changing or flipping, and diminishes the probability of arcing at the antenna since the peak voltage varies in a continuous manner along the circumference of the antenna.

Also, the frequency of the system may be varied from 50 to 800 MHz to permit scaling the diameter of chamber 16B over the range 32 in. to 2 in. without increasing the mode of operation for the preferred length $\lambda/2$. In particular, the system can be scaled upward to accommodate the increasingly large diameter wafers favored by the semiconductor industry, without changing the electromagnetic mode, by the simple expedient of decreasing the frequency within the described range and retaining low mode operation, thus avoiding the possibility of mode flipping and process changes which are associated with increasing the mode of operation.

The antenna may be fluid (liquid or gas) cooled to reduce losses associated with conductors which have resistivities that increase with temperature. For example, coolant can be flowed in one end and out the other of a tube-type antenna.

Because the high frequency of the source 26 driving the antenna is nonetheless much lower than the frequencies used in microwave or microwave-ECR applications, the optional smaller magnets operated at lower DC current by less expensive power supplies can be used, with associated smaller heat loads. In addition, as is obvious from the above discussion, co-axial cable such as 26C can be used instead of wave guides. In addition, the plasma non-uniformities caused by the $E \times B$ electron drift in other magnetic-enhanced or assisted systems are absent here, because the applied magnetic fields (both the magnetic component of the HF field applied via the antenna 25 and any static magnetic field applied by magnets 47), are substantially parallel to the electric field at the cathode. Thus, there is no $E \times B$ drift in the system.

A magnetic shunt path formed with a high permeability material may be used to allow a B field in the source (upper chamber 16A) but not at the wafer.

Optionally, permanent or electromagnets may be placed in a multi-polar arrangement around the lower chamber 16A, typically in an alternating pole north-south-north-south...north-south arrangement, to generate a multi-cusp magnetic mirror at the chamber walls. The magnets may be vertical bar magnets or preferably horizontal ring magnets, for example. Such magnets may be used to reduce electron losses to the walls, thus enhancing plasma density, without subjecting the wafer to magnetic fields.

3. TUNING ANTENNA

Typically, the antenna 25 is tuned to resonance by (1) inherent resonance, that is, by constructing the antenna to resonate at the excitation wavelength of interest; (2) varying the frequency of the generator to resonate with the antenna; or (3) a separate resonating element such as the tuning means 49, FIG. 2,

connected to the antenna for tuning the resonance. For example, element 49 can be a variable inductance-to-ground or a variable capacitor-to-ground. Referring to FIG. 2, in the presently preferred case, element 49 is a variable plate, TEFLON dielectric capacitor in which the antenna is a fixed plate and movable plate 49M is mounted on a motorized linear actuator for varying the spacing and capacitance between plates and tuning the antenna to resonance.

Alternatively, shield 44 can be moved vertically relative to the antenna 25 to vary the intervening capacitance.

Please note, inductive and capacitive tuning decreases the resonant frequency. As a consequence, it is desirable to build the system to the highest desirable resonant frequency to accommodate the decrease in resonant frequency when using capacitance or inductance tuning variables.

Automatic tuning is preferred and may be executed by using an impedance phase/magnitude detector to drive the tune/load variables. Alternatively, a reflected power bridge or VSWR bridge may be used to drive both tune and load variables, but iteration is required.

4. LOADING

Referring to FIGS. 1 and 2, conductive, capacitive or inductive load means 48 is used to match the antenna to the impedance of the RF generator 26 and the connecting co-axial cable 26C. For example, a tap or wiper may be ohmically contacted to the antenna close to or at the 50 ohm or 300 ohm or other generator output impedance location along the antenna. Alternatively, a variable inductance or a variable capacitor may be connected to the generator output impedance point 50 (FIG. 2) on the antenna. Referring to FIG. 2, in a presently preferred arrangement, a variable plate, TEFLON dielectric capacitor 48 is used. The fixed plate 48F is connected to the generator output impedance point and the movable plate 48M connected to the co-axial cable is mounted on a motorized linear actuator (not shown) for adjusting the plate spacing and capacitance. Because the impedance matching is built into the source, a matching network is not required.

5. CHAMBER CONFIGURATIONS

As alluded to above, various chamber configuration and chamber and antenna arrangements can be used. For example, a chamber may be cylindrical with a plate or window on top. The window may be located beneath and adjacent to the antenna. The presently preferred configuration and arrangement comprise the illustrated short bell-jar chamber 17 with antenna 25 circumscribing the chamber at the sides or just above the top thereof.

6. GROUND SHIELD

As disclosed, the antenna 25 sits on an associated ground plane. The ground shield or reflective cage 44 substantially completely encloses the antenna on the top and sides (360 degrees about the periphery thereof) and is open only directly beneath the antenna. The enclosure prevents the radiation of power into free space and as a consequence concentrates the radiation and the dissipation of power into the chamber plasma 16 and 16A which lies generally beneath and radially within the periphery of the antenna. As shown in FIG. 3, the distances d_1 , d_2 and d_3 between the antenna 25 and the top, side and bottom surfaces of the ground shield 44 are preferably less than a quarter wavelength ($d_1, d_2, d_3 < \lambda/4$) to avoid an unwanted resonance condition in which, without the controlled reflection, the surrounding structure or area acts as cavity resonator.

7. FARADAY SHIELD

Although various configurations of the Faraday shield are possible, the presently preferred and simplest configuration is the outwardly flanged, electrically conductive, open-ended cylinder configuration 46 depicted in FIG. 1. Preferably, the cylinder 46 has a slit or other discontinuity top-to-bottom or is sectioned or contains a multiple number of slits. The discontinuity(ies) reduces eddy current losses.

The open-ended configuration allows the axially-directed, magnetic component of the em wave from the antenna 25 to induce closed loop electric fields 39 in and parallel to the plane of the antenna which generate the plasma 39. However, the shield 46 capacitively shunts the direct electric field component to ground and prevents the direct electric field component of the high frequency electromagnetic energy from coupling to the plasma. Without the shield 46, the varying voltage along the antenna would couple to the

plasma in accordance with Maxwell's equations for capacitive displacement coupling and induce non-uniformities and gradients in the plasma density and in the energy across the wafer that would result in process non-uniformity and high energy charged particles. Faraday's Law expressed in integral form requires that a changing magnetic field through a surface results in closed electric fields in that surface.

5 Maxwell's equations that describe the phenomenon in differential form specify that the curl of the induced electric field is proportional to the negative time rate of change of the magnetic field. For sinusoidal excitation, the curl of the induced E is proportional to the radian frequency of the changing B field as well as its peak amplitude.

In short, divided or sectioned Faraday shield reduces eddy current losses, allows coupling of the high frequency, axially directed fringing magnetic field to the plasma for inducing closed loop electric fields which generate the plasma, but precludes direct coupling of the electric field (which varies along the antenna) to the plasma and, thereby, precludes any associated loss of plasma uniformity and process uniformity for high energy charged particles therefrom.

15 8. MAGNETIC ENHANCEMENT

As mentioned above, one or more (preferably, at least two) permanent or electromagnets 47-47 define a static, generally axial magnetic field orthogonal to and through both the plane of the antenna 25 and the electric fields 39 induced by the relatively high frequency RF radiating antenna. Preferably, one of three field-types is used: uniform, divergent or magnetic mirror.

Referring to FIG. 4A, a homogeneous, axial uniform magnetic field 51 applied orthogonally to the wafer 5 restricts the motion of the electrons to the walls. Because of the inability of ions to follow high frequency field variations, the ions follow the electron deficiency, and are concentrated in the plasma over the wafer. For maximum efficiency, this and other static magnetic fields can be tuned to resonance with the high frequency electromagnetic field: $\omega = 2 \pi F = Be/m$, where B is the magnetic flux density and e and m are the electron charge and mass, respectively.

An axially divergent field 52 is depicted schematically in FIG. 2. By the conservation of magnetic moment, the axial gradient of the magnetic field converts circular translational energy to axial translational energy and tends to drive the electrons and ions from the stronger field regions to the weaker regions thereof. Diverging magnetic fields can be used to push the electrons and ions from the plasma generating regions and to concentrate the plasma at the wafer.

Referring to FIGS. 4C and 4D, there are shown, respectively, a bulging or aiding magnetic field 53 (FIG. 4C) and a cusp-shaped or opposing field 54 (FIG. 4D). The effect of each of these so-called "magnetic mirror" fields is similar to that of the axially divergent field: charged particles are driven from the relatively strong field regions (at the ends here) toward the relatively weak central region.

Selectively positioning the magnet(s) and selecting and varying the strength of the fields provided by the single magnet or cooperating magnets shapes the associated uniform, diverging, or magnetic mirror field in controlled fashion to increase the density of the plasma at the wafer. For magnetic mirror fields, the preferred wafer position for maximum plasma density enhancement is closely adjacent to or at the bulge or cusp, to provide maximum plasma density enhancement.

It may be desired to utilize an axial magnetic field at the plane of the antenna to enhance plasma generation, but to eliminate the magnetic field at the wafer. An annular disk of high magnetic permeability materials (such as nickel or steel for soft iron) may be interposed below the magnet(s) and plane of the antenna but above the wafer. Optionally, multipolar confinement may be used in the lower chamber region by defining ring or bar magnets in an alternating pole arrangement.

9. CONTROL SYSTEM

The following descriptions are used here in reference to the control system depicted in FIG. 5:

Psp:	Power set point	
P _f :	Forward power	Measured by directional coupler located at /inside power supply
P _r :	Reflected power	" "
Z :	Magnitude of impedance	
<phi:	Phase of impedance	
Tsp:	Tune set point	
Lsp:	Load set point	
Tfb:	Tune feedback (measured)	
Lfb:	Load feedback (measured)	

FIG. 5 is a block diagram of an exemplary system for controlling the various components including the power supplies. Here, a system controller 500 is interfaced to antenna power supply 501, impedance bridge 502, antenna 25, bias power supply 504, impedance bridge 505, matching network 506, and cathode 32. The process parameters antenna power and DC bias, selected for ion flux density and ion energy, are supplied as input to the controller 500. Controller 500 may also control other parameters such as gas flow(s), chamber pressure, electrode or wafer temperature, chamber temperature, and others. The controller (500) may preset initial tune₁ and load₁ conditions by issuing signals on Tsp₁ and Lsp₁ lines connected to antenna 25. The controller 500 may also preset initial tune₂ and load₂ conditions by issuing signals on Tsp₂ and Lsp₂ lines connected to the matching network 506. Typically, these conditions are selected to optimize plasma initiation (gas breakdown). Power may be applied first to either the antenna 25 or to the cathode 32, or it may be applied simultaneously to both. The controller issues power set points on Psp₁ line to antenna power supply 501 and on Psp₂ line to bias power supply 504 simultaneously or sequentially (in either order).

Avalanche breakdown occurs rapidly in the gas, generating a plasma. Controller 500 monitors forward power (P_{f1}) and reflected power (P_{r1}) to/from the antenna 25, and monitors forward power (P_{f2}) and reflected power (P_{r2}) to/from the cathode 32. DC bias (cathode to anode DC voltage) is also monitored as shown by controller 500. Controller 500 adjusts the antenna tune₁ and load₁ parameters by issuing set points on lines Tsp₁ and Lsp₁, based on either (a) forward power P_{f1} and reflected power P_{r1} , or (b) impedance magnitude $|Z_1|$ and impedance phase $\angle\phi_1$. Bridge 502 furnishes impedance magnitude and phase angle information to the controller. The antenna 25 is matched when reflected power P_{r1} is substantially zero and when the impedance (magnitude and phase $|Z_1|$ and $\angle\phi_1$) is the complex conjugate of the antenna power supply output impedance. (The zero reflected power condition and the conjugate impedance condition occur simultaneously, so either reflected power may be minimized or impedances may be matched, with the same result. Alternatively, VSWR (voltage standing wave ratio) or reflection coefficient may be minimized.) Controller 500 adjusts the cathode 32 and the matching network 506 tune₂ and load₂ parameters by issuing set points on the Tsp₂ and Lsp₂ lines, based on either (a) forward power P_{f2} and reflected power P_{r2} or (b) impedance magnitude $|Z_2|$ and impedance phase $\angle\phi_2$. Bridge 505 furnishes impedance magnitude $|Z_2|$ and phase $\angle\phi_2$ information to the controller 500. Matching occurs when, similarly to antenna matching, reflected power P_{r2} is essentially zero, and when impedance (magnitude and phase $|Z_2|$ and $\angle\phi_2$) is the complex conjugate of the bias power supply 504 output impedance. DC bias is monitored by controller 500, which varies the bias power supply's output power to obtain the desired measured DC bias. Controller 500 subtracts the measured value of DC bias from the desired value of DC bias. If the difference is negative, bias power supply 504 output is increased. If the difference is positive, bias power supply 504 output is decreased (higher bias power supply 504 output generates a more negative DC bias). Proportional, proportional-integral, or proportional-integral-derivative control or other control may be used in accordance with this method.

Alternatively, instead of the preferred embodiment of adjusting bias power supply 504 output to maintain a constant DC bias, a constant bias power supply 504 output may be used.

Controller 500 may be a central controller, or a distributed system of controllers.

10. TRANSMISSION LINE STRUCTURE 32

As described in detail in the aforementioned European patent application 911129179, proper co-axial/transmission line design requires both a feed via a low characteristic impedance, short transmission line from the matching network to the wafer and a return path along the transmission line. This design requirement is satisfied by the integral transmission line structure 32 depicted in FIG. 1 which comprises the cathode 32C, concentric annular conductor 320, and a non-porous low loss insulator 32I which surrounds the cathode 32C and insulates the cathode from the concentric annular conductor 320 and displaces process gases which otherwise might break down. For example, Teflon™ or quartz materials are preferred because they have high dielectric strength, low dielectric constant and low loss. The input side of this structure is connected to the matching network in a manner described below. The insulated cathode 32C and outer conductor 320 provide separate current paths between the matching network 43 and the plasma 16. One reversible current path is from the matching network along the outer periphery of the cathode 32C to the plasma sheath at the chamber (electrode) surface. The second reversible path is from the plasma 16 along the upper inside section of chamber walls 12 then along the conductive exhaust manifold screen 29 and via the inside of the outer conductor 320 to the matching network. Please note, the exhaust manifold screen 29 is part of the uniform radial gas pumping system, and the return path for the RF current.

During application of alternating current energy, the RF current path alternates between the directions shown and the reverse directions. Due to the co-axial cable type of construction of the transmission line structure 32 and, more specifically, due to the higher internal impedance of the cathode 32C (relative to the outside thereof) and the higher impedance toward the outer surface of the conductor 320 (relative to the inner surface thereof), the RF current is forced to the outer surface of the cathode 32C and to the inner surface of the outer conductor 320, in the manner of a co-axial transmission line. Skin effect concentrates the RF current near the surfaces of the transmission line, reducing the effective cross-section of the current path. The use of large wafers, for example, wafers 4 - 8 inches in diameter and the commensurately large diameter cathode 32C and large diameter outer conductor 320 provide large effective cross-section, low impedance current paths along the transmission line structure.

Also, if the coaxial-type transmission line structure 32 were terminated in a pure resistance equal to its characteristic impedance Z_0 , then the matching network would see the constant impedance Z_0 , independent of the length of the transmission line. However, such is not the case here, because the plasma is operating over a range of pressure and power, and comprises different gases, which collectively vary the load impedance Z_1 that the plasma presents to the end of the transmission line 32. Because the load Z_1 is mismatched from the non-ideal (i.e., non-lossless) transmission line 32, standing waves present on the transmission line will increase resistive, dielectric, etc., losses between the transmission line and the matching network 31. Although the matching network 43 can be used to eliminate any standing waves and subsequent losses from the input of the matching network back to the amplifier or power supply 30, the matching network, transmission line feed 32 and plasma inside the chamber comprise a resonant system that increase the resistive, dielectric, etc., losses between the transmission line 32 and the matching network 43. In short, the load impedance Z_1 will be mismatched with losses, but losses are minimum when $Z_1 = Z_0$.

To diminish the losses due to the load mismatch, the co-axial-type transmission line structure 32 is designed to have a characteristic impedance Z_0 that is best suited to the range of load impedances associated with the plasma operation. Typically, for the above-described operating parameters (example: bias frequency range approximately 5-50 MHz) and materials of interest, the series equivalent RC load impedance, Z_1 , presented by the plasma to the transmission line will comprise a resistance within the approximate range 1 ohm to 30 ohms and a capacitance within the approximate range 50 pico farads to perhaps 400 pico farads. Consequently, as the optimum, a transmission line characteristic impedance Z_0 is selected which is centered within the load impedance range, i.e., is approximately 10 to 50 ohms.

It is necessary that the transmission line 32 be very short in order to avoid transformation of the plasma impedance that the matching network sees. Preferably, the transmission line is much less than a quarter wavelength, $\lambda/4$, and, more preferably, is about (0.05 to 0.1) λ . More generally, if it is not possible to locate the matching network at a distance much less than a quarter wavelength to the load, advantage is taken of the half wavelength periodicity associated with the impedance transformation by using a transmission line length equal to an integral multiple $n = 1, 2, 3$, etc., of a half wavelength ($\lambda/2$; λ ; $3\lambda/2$; etc.). More precisely, the preferred values are $\lambda/2$ to $(\lambda/2 + 0.05 \lambda)$;

lambda to (lambda + 0.05 lambda); 3lambda/2 to (3lambda/2 + 0.05 lambda); etc.). Under such conditions, the matching network should not be located at odd integrals of quarter wavelengths (lambda/4, 3lambda/4, 5lambda/4), because a quarter wave section (or $n\lambda/4$ where n is odd) transforms Z_1 such that $Z_{in} = Z_0^2/Z_1$, where Z_1 is typically small, producing a very large Z_{in} . The matching network then could not match to the plasma load and it would be very difficult to couple power to the plasma without unacceptable system resonance and power dissipation.

Also, for efficient coupling of power, the inside diameter (cross-section dimension) of the return conductor 320 should not be significantly larger than the outside diameter (cross-section dimension) of the center conductor 32C.

In short, the chamber incorporates a transmission line structure that couples power from the matching network 31 to the plasma 33. That transmission line structure (1) preferably is very short compared to a quarter wavelength at the frequencies of interest or, alternatively, is approximately equal to an integral half wavelength, to prevent undesirable transformation of the plasma impedance; (2) has a characteristic Z_0 selected to suppress losses due to the presence of standing waves on the line between the plasma and the matching network; and (3) uses an outside conductor path cross-sectional dimension which is not substantially larger than that of the center conductor.

11. OTHER FEATURES

A preferred feature of the invention is to automatically vary "bottom" power to maintain a constant cathode (wafer) sheath voltage. At low pressures (<500/millitorr (mt)) in a highly asymmetric system the DC bias measured at the cathode is a close approximation to the cathode sheath voltage. Bottom power can be automatically varied to maintain a constant DC bias. Bottom power has very little effect on plasma density and ion current density. Top or antenna power has very strong effect on plasma density and on current density, but very small effect on cathode sheath voltage. Therefore, it is desired to use top power to define plasma and ion current densities, and bottom power to define cathode sheath voltage.

Features which may be incorporated in the reactor chamber system 10 include, but are not limited to, the use of a fluid heat transfer medium to maintain the internal and/or external temperature of the gas inlet manifold 27 above or below a certain value or within a certain range; the use of fluid heat transfer medium to heat or cool the cathode 32C; the use of fluid heat transfer medium to heat or cool chamber walls 12 or top 13; resistive heating of the cathode 32C; the use of a gas heat transfer medium between the wafer 15 and the cathode 32C; and mechanical or electrostatic means for clamping the wafer 15 to the cathode 32C. Such features are disclosed in commonly assigned U.S. Patent No. 4,872,947, issued October 10, 1989, and commonly assigned U.S. Patent No. 4,842,683, issued June 27, 1989, which are incorporated by reference.

The inventive plasma reactor system is depicted in FIG. 1 in the conventional orientation, that is vertically, with the substrate 5 residing on an electrode 32 (cathode) and an antenna 25 located above the electrode. For convenience, we have referred to the power supplied to the antenna 25 as "antenna" or "top" power and that supplied to the electrode/cathode 32 as "bias" or "bottom" power. These representations and designations are for convenience only, and it is to be understood that the described system may be inverted, that is, configured with the electrode 32 on top and an antenna located below this electrode, or may be oriented in other ways, such as horizontally, without modification. In short, the reactor system works independently of orientation. In the inverted configuration, plasma may be generated at the antenna 25 and transported upwardly to the substrate 5 located above the antenna in the same manner as described in the specifications. That is, transport of active species occurs by diffusion and bulk flow, or optionally assisted by a magnetic field having an axial gradient. This process does not depend on gravitational forces and thus is relatively unaffected by orientation. The inverted orientation may be useful, for example, to minimize the probability of particles formed in the plasma generation region in the gas phase or on a surface, falling to the substrate. Gravity then reduces the probability of all but the smallest of such particles moving upward against a gravitational potential gradient to the substrate surface.

The chamber design is useful for both high and low pressure operation. The spacing, d , between the wafer support cathode 32C and the plane of the antenna may be tailored for both high and low pressure operation. For example, high pressure operation at 500 millitorr - 50 torr preferably uses spacing $d \leq$ about 5 centimeters, while for lower pressure operation over the range < 0.1 millitorr-500 millitorr, a spacing $d >$ 5 centimeters may be preferable. The chamber may incorporate a fixed spacing d , as shown, or may utilize variable spacing designs such as interchangeable or telescoping upper chamber sections. The reactor system 10 is useful for processes such as high and low pressure deposition of materials such as silicon oxide and silicon nitride; low pressure anisotropic reactive ion etching of materials such as silicon dioxide,

silicon nitride, silicon, polysilicon and aluminum; high pressure plasma etching of such materials; and CVD faceting involving simultaneous deposition and etchback of such materials, including planarization of wafer topography. These and other processes for which reactor system 10 may be used are described in commonly assigned European patent application 9112905.4 entitled "VHF/UHF PLASMA PROCESS FOR USE IN FORMING INTEGRATED CIRCUIT STRUCTURES ON SEMICONDUCTOR WAFERS", which is incorporated by reference.

12. APPARATUS EXAMPLES

A present working embodiment of the system incorporates the domed configuration and the antenna configuration depicted in FIGS. 1 and 2. The short quartz bell jar chamber 17 has a diameter of 6 inches. The $\lambda/2$, 200 MHz, 8-inch diameter antenna 25 is grounded at both ends, spaced about 1 inch from (below) the ground plane, and surrounds the domed processing chamber 17. Reactive load matching is supplied by the movable plate, variable capacitor tap 48, FIG. 2. Also, capacitive fine tuning of the antenna to resonance is provided by a movable plate, tuning capacitor 49. The plates of the capacitor 48 measure 1 1/4 inches by 2 1/2 inches, the fixed plate 49F is connected to the grounded end of the antenna and the spacing of the movable plate 48M is provided by a micrometer (not shown) which mounts the movable plate to the fixed plate. Plate separation is 100 mils when tuned. The open-ended (at top) Faraday shield 46 is aluminum material and grounded continuously. Reflector box 44 of material satisfies the conditions, $d_1, d_2, d_3 < \lambda/4$. Operation using high frequency RF energy of 1 kilowatt, 200 MHz provides a plasma which extends about 4 inches downstream (i.e., below) the antenna to the wafer. This provides a plasma density of $1-2 \times 10^{12}/\text{cm}^3$ and ion saturation current density of 10-15 mA/cm² downstream at the wafer. A low frequency auxiliary bias of 13.56 MHz, 200 watts applied to a 5-inch wafer positioned on the support electrode approximately 4 inches below (downstream) of the antenna provides a 200 volt cathode sheath voltage.

13. PROCESS EXAMPLES

The above-described reactor embodying my present invention is uniquely useful for numerous plasma processes such as reactive ion etching (RIE), high pressure plasma etching, low pressure chemical vapor deposition (CVD) including sputter facet deposition and planarization, and high pressure conformal isotropic CVD. Other applications include, but are not limited to, sputter etching, ion beam etching, or as an electron, ion or active neutral plasma source.

RIE and low pressure CVD typically use pressures of up to 500 mt (millitorr). High pressure plasma etch and high pressure conformal isotropic CVD processes may be carried out at pressures from about 500 mt to about 50 torr.

(a) Reactive Ion Etching (RIE)

In accordance with the invention, silicon oxide, silicon (single crystal silicon), polysilicon (polycrystalline silicon), aluminum and other materials can be etched in an RIE mode. For this purpose, the high frequency em (electromagnetic) energy is coupled to the plasma by the substantially closed loop antenna 25. Typically, relatively lower frequency AC energy is applied to the cathode 32 (the wafer support electrode or cathode). The high frequency antenna power is selected to obtain the desired ion flux density, and the lower frequency AC bias power is selected to independently control the desired cathode sheath voltage and, thus, the ion energy. Please note, in low pressure applications, that is, those involving pressures within the approximate range 0.1 - 500 millitorr, the cathode or wafer sheath voltage closely approximates the DC bias of the cathode and, as a consequence, bias voltage measurements may be used to monitor the cathode or wafer sheath voltage values.

Typically, the useful high frequency em energy range is 50-800 MHz, the preferred useful range 50-400 MHz and the most preferred range 50-250 MHz. Relatively low frequency AC energy (bias energy) ranges are 10 KHz - 50 MHz, 100 KHz - 30 MHz and 5-15 MHz. Unless otherwise specified, the frequency and pressure ranges specified previously in this numbered section apply to the process parameters specified in

* 1 Torr = 1.33 mbar

* 1 mil = .001 inch, 1 inch = 2.54 cm

the RIE tables below. The useful, preferred and most preferred ranges correspond generally to the ranges 1, 2 and 3 in the tables.

RIE Example 1: Silicon Oxide over Polysilicon (Contact Window Hole Etch)

As a first example of the RIE of silicon oxide, consider forming contact window holes through oxide to underlying polysilicon gates. This application is occasioned by a multiplicity of requirements, including no damage to the polysilicon gates or to the underlying gate oxide; no microloading; high oxide/poly selectivity (20/1); vertical oxide etch profile; and high oxide etch rate (typical oxide thicknesses are ≥ 1 micron). The high selectivity requires approximately 500 eV ion energy in the etching plasma.

As is known to those of usual skill in the art, suitable gas chemistries for etching contact window holes in oxide comprise fluorine as the main etchant for providing a high etch rate, and may include carbon- and hydrogen-containing gases for enhancing etch selectivity. Specific gases used include CHF_3 , CF_4 , C_2F_6 , C_4F_8 , CH_4 , H_2 , NF_3 , and SF_6 . Preferred carbon to fluorine ratios are $\text{C/F} = 0.1/1 - 2/1$ and, when hydrogen is present, the preferred hydrogen to fluorine ratios are $\text{H/F} = 0.1/1 - 0.5/1$. Argon is a preferred inert gas dopant, because it is relatively massive and inert and, thus, contributes to the sputter etch components of the RIE process, improving the vertical anisotropy.

Using 1 kW, 200 MHz high frequency power ("antenna" or "top" power); 600 watts, 13.56 MHz auxiliary bias ("bottom" or "bias" power); 10-30 millitorr pressure; the gas chemistry $\text{CHF}_3/\text{argon}$ and gas flow rates 100 sccm/120 sccm provides oxide etch rates of 5,000-7,000 Angstroms/minute with an oxide-to-poly selectivity of 20/1.

Table 1 summarizes typical contact window etch processes which satisfy the above-described rigid etch requirements.

RIE Example 2: Silicon Oxide over Metal (Via Hole Etch)

As a second example of RIE etching of silicon oxide, consider via hole etching through a silicon oxide layer to an underlying aluminum conductor layer or other metal layer. Here, the critical multiple requirements include no damage to the underlying devices; no damage (i.e., no sputtering) of the underlying aluminum; a vertical oxide etch profile; and a high oxide etch rate. A suitable gas chemistry for these purposes includes fluorine compounds and, typically, carbon. Hydrogen may be used to improve oxide/photoresist etch selectivity. Specific gases used include CHF_3 , CF_4 , C_2F_6 , C_4F_8 , CH_4 , H_2 , NF_3 , and SF_6 . Preferred ratios are $\text{C/F} = 0.1/1 - 2/1$ and, when H is present, $\text{H/F} = 0.1/1 - 0.5/1$. As in the previous oxide example, argon is the preferred inert gas additive, because it is relatively massive and thus contributes to the sputter etch (of the oxide) component of the RIE process, improving the vertical anisotropy of the process. Also, a low cathode sheath voltage, typically ≤ 300 volts, is desirable to avoid sputtering the aluminum. Preferably, the voltage is ≤ 200 volts and most preferably about 100-150 volts. Using top power of 1.5 kW and 200 MHz; pressure of 10-30 millitorr; reduced bias or bottom power of about 200 watts at 13.56 MHz to provide a 200 volt cathode sheath voltage; and $\text{CHF}_3/\text{CF}_4/\text{argon}$ gas chemistry at flow rates of 75/75/120 sccm etches vertical-wall via holes at a rate of 4,000-5,000 Angstroms/minute without sputtering of the aluminum. Other chemistries may be used as known by those skilled in the art, such as CF_4 , C_2F_6 , C_4F_8 , CH_3F , CH_4 which may be used in various combinations.

Table 2 discloses silicon oxide etch processes which are well suited to etching via holes. The representative cathode bias voltages disclosed in Table 2 provide the desired cathode sheath voltages.

RIE Example 3: Oxide Sputter Etch

Table 3 specifies typical processing parameters for effecting a third type of non-reactive ion etch oxide etch process, oxide sputter. This process is useful for the etchback of deposited films and removal of native oxide on silicon using a relatively non-reactive gas, preferably argon.

RIE Example 4: Selective Polysilicon Etch (Etch Poly Gate Selectively to Oxide)

RIE etching of polysilicon and in particular selective etching of polysilicon with respect to oxides such as underlying oxide layers, requires an etch process characterized by no damage (to interconnects, gates and gate oxides); no microloading; vertical polysilicon etch profile; a high poly/oxide etch selectivity (typically $\geq 30/1$); and a moderate etch rate (poly thicknesses are 2,000-5,000 Angstroms). Referring to Table 4, suitable gas chemistries for achieving these goals include halogen-containing gases compounds.

At conventional etch temperatures, > about 0°C, chlorine or bromine chemistry is preferred. Below about -40°C, fluorine chemistry can be used. Optionally, an inert gas(es) such as argon or helium may be added to the gas chemistry to enhance the vertical etch anisotropy. Other dopant gases such as oxygen may be added to improve the poly/oxide etch selectivity. As is true of the above-described RIE etching of oxide over aluminum, a low cathode sheath voltage (< 200 volts; < 100 volts; 50-100 volts); is preferred to obtain high poly silicon/oxide etch selectivity.

The following process parameters provide a polysilicon gate-forming etch rate of 3,000-4,000 Angstroms/minute with a 35/1 selectivity of polysilicon/oxide: 500 watts at 200 MHz top power operated at resonance; bottom power of 100 watts at 13.56 MHz, providing a low cathode sheath voltage of approximately 75 volts; pressure 10-50 millitorr; and etching gas chemistry Cl₂/He/O₂ (oxygen optional) at flow rates of 80 sccm/400 sccm/(0-4 sccm). Other chlorine sources such as BCl₃ may be used.

RIE Example 5: Aluminum Etch

Table 5 depicts the process parameters for RIE etching of aluminum which satisfy the requirements that there be no damage to underlying devices and no corrosion of aluminum and that the process provide a high aluminum etch rate (typically 5,000-10,000 Angstroms/min.). Suitable gas chemistries include chlorine- and bromine-containing gases, alone or in combination. Relatively non-reactive/inert gases such as argon may be added for the purpose of profile control. To minimize corrosion of aluminum after etch by chlorinated species, a photoresist strip and Al fluorine passivation can be performed in the same or another chamber.

RIE Example 6: Single Crystal Silicon Etch

Table 6 depicts the representative proven parameters for RIE etching of single crystal silicon in accordance with the process requirements that there be no damage (lattice damage results from high energy bombardment in conventional RF systems) and that the process provide a vertical silicon etch profile, i.e., a high aspect ratio (l/w). The gas chemistry includes halogen species and preferably both bromine and fluorine species (e.g., HBr + SiF₄ or HBr + SiF₄ + NF₃) for profile control as well as dopants such as helium and oxygen, also for profile control (HBr/SiF₄/NF₃/O₂/He).

RIE Example 7: Tungsten Etch

Table 7 discloses the process parameters for RIE etching tungsten without damage to underlying devices. The process is based upon a gas chemistry which comprises a fluorine-containing gas such as NF₃ or SF₆ and, optionally, inert gas such as argon for the purpose of increasing the sputter etch component.

RIE Example 8: Anisotropic Photoresist Etch

Anisotropic RIE etching of photoresist may be used, for example, for patterning resist for advanced devices. Process requirements are vertical etch profile and no damage to underlying devices. Table 8 discloses the parameters for anisotropic patterning of photoresist using RIE. The associated gas chemistry comprises oxygen and, optionally, fluorine-containing gas such as CF₄, C₂F₆, NF₃ and/or SF₆. The wafer is maintained at a low temperature, preferably < 125°C, and most preferably < 75°C, to avoid photoresist reticulation. As discussed previously in the apparatus disclosure, fluid cooling of the wafer support electrode/cathode/pedestal can be used to provide the necessary temperature control.

Anisotropic profiles are etched in photoresist using top power of 1 kW at 200 MHz; pressure of 10-30 millitorr; gas chemistry and associated flow rates of 30-100 sccm O₂ and 10-50 sccm CF₄ (optional); a bottom bias of 0-200 watts at 13.56 MHz; and a cathode temperature of about 60 degrees C. The process provides an anisotropic photoresist etch rate of 0.8-3 μm/minute

RIE Example 9: Barrier Layer Etching

Barrier layers of material such as titanium, tungsten or titanium nitride are thin layers formed between layers of material such as oxide and aluminum. For example, barrier layers can be used to prevent damage/etching of aluminum during the formation of via holes in overlying oxide layers. The barrier layer must be removed after the oxide via etch and prior to filling the via to permit proper ohmic contact to the

aluminum. The critical features of such a barrier layer etch process include no damage to underlying layers or devices, for example, by sputtering the underlying aluminum. Table 9 discloses the process parameters for a halogen-based gas chemistry comprising chlorine-containing and fluorine-containing constituents.

5 b) Light Etch

A so-called light oxide etching is used after a main oxide etch step, to remove damaged thin layers of material such as oxide or polysilicon, without incurring additional damage. My light etch satisfies the requirements of removing damaged removal without additional damage in part by providing downstream etching (at the wafer support electrode/cathode) using low bombardment energies. Table 10 shows a suitable light oxide etch process which uses fluorine-containing gas chemistry. The light oxide etch process of Table 10 can be changed to a light etch process for polysilicon by substituting a chlorine-containing constituent gas such as Cl_2 for the fluorine-containing gas.

In one specific example, top power of 200-1,000 watts at 200 MHz; no bias or bottom power; 10-50 millitorr pressure; and 30-120 sccm CF_4 provides a low energy oxide etch rate of 100-1,000 Angstroms/minute.

c) High Pressure Plasma Etch

In accordance with the invention, silicon oxide, polysilicon, photoresist and other materials can be etched in a high pressure plasma etch mode. Certain basic features and operation are as described above in the first paragraph under the section 11 heading. Specifically, the high frequency em energy is coupled to the plasma by the substantially closed loop antenna. Relatively lower frequency AC energy may be applied to the cathode (the wafer support electrode/cathode) as required. The high frequency antenna power is selected to obtain the desired ion flux density and the lower frequency AC bias power is selected to independently obtain and control the desired cathode sheath voltage and, thus, ion energy.

Profile control is possible during the high pressure etch by selecting the bias power and pressure as follows. At high pressure (1-50 torr) and low bias power (0-200 W), the process may be isotropic or semi-anisotropic horizontally. By increasing the bias power (200 W - 1,000 W) and/or decreasing the pressure (500 mt - 1 torr), the etch process may be semi-anisotropic vertically or anisotropic vertically. In general, increasing/decreasing bias power increases/decreases vertical anisotropy, while decreasing/increasing the pressure increases/decreases vertical anisotropy. Typically, useful antenna and bias frequencies are, respectively, 50-800 MHz and 10 KHz - 50 MHz, while more preferred useful ranges are 50-400 MHz and 100 KHz - 30 MHz, and presently the most preferred ranges are 50-250 MHz and 5-15 MHz.

35 High Pressure Plasma Etch: Isotropic Oxide Etch

FIG. 6 depicts the structure which exists after contact or via holes 601 are etched through an oxide layer 603 to underlying conductor 602 using the photoresist pattern definition mask 604. As integrated circuit devices become increasingly small and features such as the via holes 601 become correspondingly narrower, filling the hole becomes increasingly difficult. Referring to FIG. 7, the aluminum fill is made easier by first widening the top of the hole, as indicated at 606, FIG. 7. The widening step requires an etch process that has a horizontal etch component. In addition, it is desirable that this etch step not damage the integrated circuit components. The process described in Table 11 satisfies these requirements and, thus, is ideally suited to the application depicted in FIG. 7 as well as to other applications requiring directional control.

Furthermore, as alluded to above, bias power and pressure may be selected to vary the etch directionality from preferentially horizontal using relatively high pressure (3-50 torr) with no bias or very low bias, to isotropic at moderate pressure (1-3 torr) and no to low bias (0-200 W), to preferentially vertical at lower pressure (500 mt - 1 torr) and higher bias (200-1,000 W). As indicated in Table 11 wafer temperatures are maintained below 125°C for the purpose of preventing photoresist reticulation and the resultant loss of pattern definition.

Using top power of 1-1.5 kW at 200 MHz; pressure of about 1 torr; 500 sccm - 2,000 sccm NF_3 or CF_4 ; and a cathode temperature of about 60-75 degrees C provides an isotropic silicon oxide etch rate of about 2,500-4,500 Angstroms/minute.

Photoresist Strip

Stripping thick photoresist masks requires high photoresist etch rates without damage to associated integrated circuit components and without etch residue. A downstream process is preferred. Table 12 depicts a suitable process which is based upon a gas chemistry comprising oxygen as the main photoresist etchant and, optionally, including nitrogen for the purpose of increasing strip rate and/or preferably fluorine-containing gas for passivation (of aluminum). The wafer temperature is controlled to below 300°C for the purpose of avoiding resist reticulation. In addition, the third example (range 3) in the table effects fluorine passivation.

A fast downstream photoresist strip process uses top power of 1-1.5 kW at 200 MHz; (no bias or bottom power); pressure of about 1 torr; etching gas chemistry and flow rates of 800-1,000 sccm O₂, 100-200 sccm N₂ (optional) and 0-100 sccm CF₄ (optional); and a cathode temperature of 100-200 degrees C (the strip rate is temperature dependent) and provides a strip rate of 1-3 μm per minute.

12. CHEMICAL VAPOR DEPOSITION (CVD)

In accordance with the invention, low pressure chemical vapor deposition (LPCVD) may be used to deposit various materials including silicon oxide, boron- and phosphorous-doped oxide (including borosilicate glass (BSG), phosphosilicate glass (PSG) and borophosphosilicate glass (BPSG)) and plasma nitride. The antenna, bias and pressure ranges for effecting CVD (chemical vapor deposition) are similar to those used for the above-described RIE etching processes. That is, the high frequency em energy coupled to the plasma has a useful frequency range 50-800 MHz, preferred useful range 50-400 MHz, and presently preferred range 50-250 MHz. The relatively lower frequency AC energy is applied when required to the wafer support electrode/cathode using ranges of 10 KHz - 50 MHz, 100 KHz - 30 MHz and 5-15 MHz. The high frequency antenna power is selected to obtain the desired ion flux density and the lower frequency AC bias power is selected to independently obtain and control the desired cathode sheath voltage and, thus, ion energy. Preferably, pressure is in the range 0.1-500 mt and, more preferably, 1-100 mt.

Also in accordance with invention, high pressure chemical vapor deposition (HPCVD) may be used to deposit various materials including those discussed in the previous paragraph using the high frequency antenna energy and the low frequency bias energy described in the preceding paragraph, but typically using pressure > 500 millitorr.

In the HPCVD application, the high frequency em energy is coupled to the plasma by the substantially closed loop antenna and the relatively lower frequency AC energy is applied to the wafer support electrode. Here, the high frequency power is selected to obtain the desired plasma density and the lower frequency AC bias power is selected to independently obtain and control the desired cathode sheath voltage and thus ion energy. For HPCVD processes, both radical and ion flux densities are important. The high pressure is used to vary the ratio of the radical deposition component to the ion deposition component. Relatively higher pressure (5-50 mt) and lower bias (0-200 mt) generate more radicals with respect to ions and lower bias yields less ion directionality. Relatively lower pressures of about 500 mt - 5 torr and higher biases generate less radicals with respect to ions, and higher bias of about 200-1,000 W yields more ion directionality. By controlling these parameters, the degree of deposited film conformality can be varied, from slightly preferentially horizontal under conditions of high pressure, no bias; to isotropic using very low bias to no bias, moderate pressure; to preferentially vertically at lower pressure, higher bias. Preferentially horizontal pressure 10-50 tort, no bias; isotropic pressure 5-10 tort, bias 0-200 W; and preferentially vertical pressure 500 mt - 5 torr, bias 200-1,000 W.

45 (a) Low Pressure CVD

1) Plasma Nitrides and Plasma Oxynitrides

Applications of plasma nitride and plasma oxynitride include as passivation layers and intermetal dielectrics. In such applications, the associated deposition process must not damage devices. When used to form passivation layers, the process must provide good moisture barrier with stress control and when used to deposit an intermetal dielectric, it must provide step coverage, high dielectric strength, controlled physical properties (stress), electrical properties (dielectric strength and dielectric constant), optical properties (absorption spectrum) and chemical properties (hydrogen content). Please note, typically plasma nitride and plasma oxynitride are not stoichiometric; rather, the deposited nitride materials are Si-H-N and the oxynitride materials are Si-H-O-N.

Typically, the gas chemistry comprises silane and nitrogen when low hydrogen content nitride is required, or silane, nitrogen and ammonia where higher hydrogen content can be tolerated, or the same

considerations apply to oxynitride except that the gas chemistry includes an oxygen-containing gas such as nitrous oxide or oxygen itself, and typically a lower nitrogen flow rate. The corresponding processes for plasma nitride deposition and for plasma oxynitride deposition are summarized below, respectively, in Tables 13 and 14.

2) LPCVD Oxide

Applications for LPCVD silicon oxide include intermetal dielectrics. Critical process requirements include no damage to underlying devices, gap-filling capability, high rate deposition and control of physical, electrical, optical and chemical properties, as described in greater detail above with respect to LPCVD plasma nitride. Typically, the gas chemistry for the process includes a silicon-containing gas (such as silane or TEOS), an oxygen-containing gas (oxygen itself or nitrous oxide) and, optionally, an inert gas (typically, argon). Additional boron and phosphorous dopants may be used to provide BSG, PSG and BPSG glasses, and arsenic dopant may be added for the purpose of, for example, improving step coverage. The relevant process is summarized in Table 15.

One variation on the above LPCVD oxide process is bias sputter deposition, which is a two-step process. First, the process of Table 15 is used, but with no bottom bias, to deposit a thin oxide layer while ensuring that the aluminum is not sputtered. Second, bottom bias and argon flow are added as indicated in Table 15 to effect sputter facet deposition.

In a third variation, silicon oxide planarization may be effected by modifying the bias sputter deposition process so that the ratio of unbiased deposition rate to sputter etch rate is selected to planarize the wafer topography. The sputter etch rate is determined by the bias and pressure while the unbiased deposition rate is determined by antenna power and reactant species. Consequently, the ratio is determined by selecting the four factors, bias power, pressure, antenna power and reactant flow rates.

In a fourth variation, the silicon oxide planarization can be extended to provide a global or large area planarization process by incorporating materials such as B_2O_3 which readily flows during the deposition process and fill large areas between features. For the exemplary B_2O_3 , the associated gas chemistry is TMB (trimethylborate) and O_2 (optional inert gas (He)).

3) CVD Low Pressure (Facet) Deposition

In this process, sometimes known as a CVD facet process, etching of the materials (e.g., oxide or nitride) deposited on the outside (upper) corners of a trench in the silicon wafer is also carried out simultaneously with the deposition of oxide or nitride into the trench to avoid formation of voids in the filler material. In the prior art, such faceting and deposition was carried out simultaneously in ECR/microwave frequency plasma CVD. The prior art use of plasma-assisted CVD at high frequencies, such as 13.56 MHz, resulted in the need for cycling the wafer between a deposition chamber and an etching chamber to achieve the desired faceting.

In accordance with the invention, simultaneous low pressure CVD deposition and faceting may be carried out using a plasma-assisted CVD process wherein the plasma is energized by a resonant circular antenna operating in a frequency range of about 50 MHz to 800 MHz and, preferably, in a frequency range of from about 50 MHz up to about 250 MHz. Wafer bias is applied to effect sputter faceting. The use of complicated microwave/ECR equipment, and the need for cycling the wafer between deposition and etching chambers, are avoided.

Additionally, planarization of the wafer topography may be performed by selecting the ratio of unbiased deposition rate to sputter etch rate based on device/feature geometry. It may be combined with deposition of such materials as B_2O_3 which flow during the deposition process to globally planarize the wafer.

(b) High Pressure CVD

1) Conformal Isotropic Plasma Nitride And Plasma Oxynitride

Like their LPCVD counterparts, the high pressure CVD, conformal, isotropic plasma nitride and oxynitride processes have application such as to passivation layers and intermetal dielectrics. The requirements and gas chemistries discussed above relative to their LPCVD counterparts apply here as well. In the HPCVD process, bias power is used to control film density and stress. The processes for depositing low hydrogen nitride ($SiH_4 + N_2$) and conventional higher hydrogen plasma nitride (silane + nitride + ammonia) are summarized in Table 16.

Table 16 can be used for the deposition of low hydrogen content oxynitride and higher hydrogen content oxynitride by incorporating an oxygen source (oxygen or, preferably, nitrous oxygen) in the gas chemistry. The same N₂ flow rates are used for oxynitride and nitride.

5 2) Conformal Isotropic Silicon Oxide

The applications and associated requirements for this HPCVD process are similar to those for the LPCVD counterpart, with the possible exception that the LPCVD process is more suitable to filling gaps the HPCVD process may be favored for step coverage applications. My present HPCVD process uses a gas chemistry comprising silicon-containing species (typically, silane or TEOS (tetraethylorthosilicate or tetraethyloxysilicate)), an oxygen-containing species (typically, oxygen itself or preferably nitrous oxide) and, optionally, an inert gas (typically, argon). The overall HPCVD process for depositing conformal silicon oxide is summarized in Table 17.

The above examples are representative. Those of usual skill in the art will readily extend the examples to achieve isotropic and anisotropic etching of various materials.

Table 1
OXIDE CONTACT WINDOW ETCH
OXIDE/POLY

Parameter	Range		
	1	2	3
Antenna power (W)	300-5000	500-2500	800-2000
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	100-1000	200-1000	400-800
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500	1-100	5-50
Wafer temp. (°C)	≤ 125	-	-
Gas Chemistry (sccm)			
Etchant	CF=0.1/1-2/1	CHF ₃ 30-600	50-300
Dopant	HF=0.1/1-0.5/1	Ar 30-600	50-300

Table 2
OXIDE VIA HOLE ETCH
OXIDE/ALUMINUM

Range

<u>Parameter</u>	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	100-5000	300-2500	800-2000
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	100-1000	100-500	100-300
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Cathode Sheath (V)	≤ 300	≤ 200	5-50
Press. (mt)	≤ 500	1-100	5-50
Wafer temp. ($^{\circ}\text{C}$)	≤ 125	-	-
Gas Chemistry (sccm)			
Etch	CF=0.1/1-2/1	CHF ₃	50-300
	HF=0.1/1-0.5/1	CF ₄	50-300
		Ar	50-300

Table 3
OXIDE SPUTTER ETCH

<u>Parameter</u>	<u>Range</u>		
	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	300-5000	500-2500	800-2000
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	100-800	100-300
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500	1-100	1-30
Wafer temp. (°C)	-	-	-
Gas Chemistry (sccm)			
Etchant	Non-reactive	Ar	Ar

Table 4
POLY/OXIDE

Parameter	Range		
	1	2	3
Antenna power (W)	200-1500	300-1000	300-750
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-500	0-300	0-200
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Cathode Sheath (V)	≤ 200	≤ 100	50-100
Press. (mt)	≤ 500	1-100	5-50
Wafer temp. (°C)	(1) $> -40^{\circ}\text{C}$ (2) $< -40^{\circ}\text{C}$		
Gas Chemistry (sccm)			
Etch (1)	Cl or Br	Cl ₂ or HBr or BCL ₃ + Ar	Cl ₂ 50-300 He 50-300 O ₂ 0-20
(2)	F	SF ₆ or NF ₃ + Argon	SF ₆ 30-300 Ar 30-300

Table 5
RIE ALUMINUM

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Range

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Parameter**1****2****3****Antenna
power (W)**

500-1500

600-800

600-800

**Antenna
freq. (MHz)**

50-800

50-400

50-250

**Bias power
(W)**

100-400

100-200

100-200

Bias freq.10 KHz -
50 MHz100 KHz -
30 MHz

5-15 MHz

Press. (mt) ≤ 500

1-100

5-50

**Wafer temp.
(°C)** ≤ 125

-

**Gas Chemistry
(sccm)****Etch** Cl_2/BCl_3 $\text{Cl}_2 + \text{BCl}_3$ Cl_2 30-100 BCl_3 30-100**Dopant** BBr_3

Table 6
RIE SILICON

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Range

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<u>Parameter</u>	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	100-2500	300-700	300-700
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-500	50-200	50-150
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500	5-50	5-50
Wafer temp. (°C)	≤ 125	≤ 100	≤ 75
Gas Chemistry (sccm)			
Etchant	Halogen	HBr/SiF ₄ /NF ₃	HBr 30-100 SiF ₄ 0-20 HBr 0-10
Dopant		He/O ₂	O ₂ 0-10 NF ₃ 0-20

Table 7
RIE TUNGSTEN

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Range

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<u>Parameter</u>	<u>1</u>	<u>2</u>
Antenna power (W)	100-2500	200-500
Antenna freq. (MHz)	50-800	50-250
Bias power (W)	0-500	0-200
Bias freq.	10 KHz - 50 MHz	5 MHz - 15 MHz
Press. (mt)	≤ 500	10-100
Wafer temp. (°C)	-	-
Gas Chemistry (sccm)		
Etchant	F	NF ₃ 0-200 SF ₆ 0-200
Dopant	Inert	Ar 0-200

Table 8
ANISOTROPIC RIE PHOTORESIST

Parameter	<u>Range</u>		
	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	300-2500	300-1500	300-1500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-500	0-300	0-200
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500	1-100	5-50
Wafer temp. (°C)		≤ 125	≤ 75
Gas Chemistry (sccm)			
Etchant	O	O ₂	O ₂ 10-300
Dopant	F	CF ₄	CF ₄ 0-300

Table 9
RIE BARRIER LAYER
TiW/TiN

Range

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<u>Parameter</u>	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	100-2500	300-1000	300-600
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-500	0-200	100-200
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500	1-100	5-50
Wafer temp. (°C)			
Gas Chemistry (sccm)			
Etch	Halogen	F + Cl	CF ₄ 0-20 BCl ₃ 10-100 Cl ₂ 0-20

Table 10
LIGHT ETCH

<u>Parameter</u>	<u>Range</u>	
	<u>1</u>	<u>2</u>
Antenna power (W)	100-1000	100-1000
Antenna freq. (MHz)	50-800	50-250
Bias power (W)	0-200	0-200
Bias freq.	10 KHz - 50 MHz	5-15 MHz
Press. (mt)	≤ 500	5-100
Wafer temp. (°C)	-	-
Gas Chemistry (sccm)		
Oxide	F	CF ₄ 30-120
		or NF ₃ 30-120
Poly	Cl	Cl ₂ 30-120

Table 11
HP ISOTROPIC OXIDE ETCH

Parameter	Range		
	1	2	3
Antenna power (W)	500-5000	500-2500	500-2500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-500	0-300	0-300
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500 mt	0.5-20 torr	0.5-5 torr
Wafer temp. ($^{\circ}$ C)	≤ 125	≤ 100	60-75
Gas Chemistry (sccm)			
Etch	F	CF ₄	CF ₄ 500-2000
		NF ₃	or NF ₃ 500-2000
		SF ₆	
		C ₂ F ₆	

Table 12
PHOTORESIST STRIP

Parameter	Range		
	1	2	3
Antenna power (W)	300-5000	300-2500	300-2500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	0-1000	0-1000
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5 - 15 MHz
Press. (mt)	100 mt - 50 torr	500 - mt 10 torr	500 mt - 5 torr
Wafer temp. (°C)	≤ 300	≤ 250	100-200
Gas Chemistry (sccm)			
Etchant	O	O ₂ , N ₂ O	O, N ₂ O 500-2000
Dopant	F, N	CF ₄ , NF ₃ , SF ₆ , C ₂ F ₆	N ₂ 0-5000 CF ₄ 0-500 NF ₃ 0-500

Table 13
LP PLASMA NITRIDE DEPOSITION

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<u>Parameter</u>	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	300-5000	300-2500	300-2500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	0-600	0-600
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5 - 15 MHz
Press. (mt)	≤ 500	≤ 50	≤ 50
Wafer temp. (°C)	-	100-500	200-400
Gas Chemistry (sccm)			
	Si & N	SiH ₄	30-300
		N ₂	100-1000
		NH ₃	0-50

Table 14
LP PLASMA OXYNITRIDE DEPOSITION

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Parameter	1	2	3
Antenna power (W)	300-5000	300-2500	500-2500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	0-600	0-600
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5 - 15 MHz
Press. (mt)	≤ 500	≤ 50	≤ 50
Wafer temp. (°C)	-	100-500	200-400
Gas Chemistry (sccm)			
Si	Si	SiH ₄	30-300
N	N	N ₂	100-1000
O	O	O ₂ /N ₂ O	100-1000
Dopant		NH ₃	0-50

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Table 15
LP OXIDE DEPOSITION

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<u>Parameter</u>	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	300-5000	500-2500	1000-2000
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	200-1000	200-1000
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5-15 MHz
Press. (mt)	≤ 500	1-100	1-30
Wafer temp. (°C)	≤ 500	200-400	300-400
Gas Chemistry (sccm)			
	Si	SiH ₄ /TEOS	SiH ₄ 30-100
	O	O ₂ /N ₂ O	O ₂ 30-200
Dopant	Inert	Ar	Ar 400-800

Table 16
HP OXIDE/OXYNITRIDE DEPOSITION

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<u>Parameter</u>	<u>1</u>	<u>2</u>	<u>3</u>
Antenna power (W)	300-5000	300-2500	500-1500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	0-300	0-300
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5 - 15 MHz
Press. (mt)	≥ 500	500 mt - 50 torr	1-10 torr
Wafer temp. (°C)	-	100-500	200-400
Gas Chemistry (sccm)			
Nitride	Si	SiH ₄	30-100
	N	N ₂ O	400-5000
		NH ₃	0-30
Oxynitride	Si	SiH ₄	30-100
	N	N ₂	400-5000
	O	N ₂ O	400-5000
		O ₂	-
		NH ₃	0-30

Table 17
HP CONFORMAL OXIDE DEPOSITION

Parameter	1	2	3
Antenna power (W)	300-5000	300-2500	500-1500
Antenna freq. (MHz)	50-800	50-400	50-250
Bias power (W)	0-1000	0-1000	0-1000
Bias freq.	10 KHz - 50 MHz	100 KHz - 30 MHz	5 - 15 MHz
Press. (mt)	> 500	500 mt - 50 torr	500 mt - 10 torr
Wafer temp. (°C)	-	100-500	200-400
Gas Chemistry (sccm)			
	Si	SiH ₄ + N ₂ O	30-100 + 200-3000 SiH ₄ + N ₂ O
	O	TEOS + O ₂	30-100 + 100-1000 TEOS O ₂
		TEOS + N ₂ O	30-100 + 100-1000 TEOS N ₂ O

Inert

Claims

1. A process for forming a plasma, comprising: supplying gas to a vacuum chamber while applying elliptically polarized high frequency electromagnetic energy to the chamber to generate a plasma from the gas for fabricating a selected material.
2. A process for generating a plasma, especially according to claim 1, comprising supporting an object on an electrode within a vacuum chamber; supplying gas to the vacuum chamber; using a substantially closed loop antenna adjacent to the chamber, generating high frequency electromagnetic energy; and coupling the electromagnetic energy into the chamber thereby generating a plasma for fabricating one or more materials on the object.
3. The process of claim 1 or 2, the direct electric field component of the electromagnetic energy being shielded from the chamber and the magnetic component of the electromagnetic energy being coupled into the chamber for generating the plasma.

4. The process of one of the preceding claims, the magnetic component of the electromagnetic energy being coupled into the chamber, for inducing elliptical electric fields to generate the plasma.
5. The process of claim 4, wherein the coupled component induces circular electric fields.
- 5 6. The process of one of the preceding claims, further comprising applying AC energy of selected frequency to the electrode for controlling cathode sheath voltage.
7. The process of claim 6, further comprising varying the power delivered to said electrode for maintaining selected cathode sheath voltage.
- 10 8. The process of claim 5 or 6, whereby high ion flux is produced at low ion energy independently of cathode sheath voltage and wherein the power delivered to the antenna defines ion flux density and the power delivered to the electrode defines cathode sheath voltage, for directing ions and controlling ion energy independently of ion flux density.
- 15 9. The process of one of the preceding claims, wherein the gas comprises an etchant gas and the plasma produces etchant species.
- 20 10. The process of one of the preceding claims, wherein the gas comprises a deposition gas and the plasma produces deposition species.
11. The process of claim 9 or 10, further comprising controlling the antenna power and the bias power delivered to the electrode for selectively effecting anisotropic, semi-anisotropic and isotropic etching and/or deposition.
- 25 12. The process of one of claims 2 to 11, wherein the object is a semiconductor wafer and the plasma is generated from the gas for fabricating one or more materials on the semiconductor wafer.
- 30 13. The process of claim 12, wherein fabricating comprises etching one or more materials.
14. The process of claim 12, wherein fabricating comprises depositing one or more materials.
15. The process of claim 12, wherein fabricating comprises separately or simultaneously depositing and etching one or more materials.
- 35 16. The process of one of the preceding claims, further comprising applying bias energy to the wafer support electrode to control the wafer sheath voltage.
- 40 17. The process of one of the preceding claims, wherein the material is oxide or polysilicon.
18. The process of one of claims 2 to 17, comprising etching, preferably isotropically etching, a layer of oxide by applying high frequency power to the antenna.
- 45 19. The process of one of claims 2 to 18, comprising etching a layer of oxide by applying relatively high frequency power to the antenna and relatively lower frequency power to the wafer support electrode.
20. The process of claim 19, whereby the layer of oxide is anisotropically etched.
- 50 21. The process of claim 16, wherein the material etched is oxide formed on poly, comprising applying antenna power of 300 to 5000 watts at 50 to 800 MHz; bias power of 100 to 1000 watts; gas chemistry and the combination comprising one or more of fluorine-, carbon- and hydrogen-containing gas and comprising fluorine-, carbon- and hydrogen-containing gas and inert gas; and pressure less than about 500 millitorr*.
- 55 22. The process of claim 16, wherein the material etched is oxide formed on poly, comprising applying

* 1 millitorr = 1.3×10^{-4} bar

- antenna power of 500 to 2500 watts at 50 to 400 MHz; bias power of 200 to 1000 watts; gas chemistry selected from (1) the combination comprising one or more of fluorine-, carbon-, and hydrogen-containing gas and (2) the combination comprising one or more of fluorine-, carbon- and hydrogen-containing gas and inert gas; and pressure within the range of about 1 millitorr to about 100 millitorr.
- 5
23. The process of claim 16, wherein the material etched is oxide formed on poly, comprising applying antenna power of 800 to 2000 watts at 50 to 250 MHz; bias power of 400 to 800 watts; gas chemistry comprising one or more gases selected from CHF_3 , CF_4 , C_2F_6 , C_4F_8 , CHF_3 , CH_3F , CH_4 , hydrogen, oxygen and inert gas; and pressure within the range of about 5 millitorr to about 50 millitorr, for etching the oxygen at 2500 to 10,000 Angstroms/minute**.
- 10
24. The process of claim 16, wherein the material is oxide over polysilicon and wherein the gas chemistry comprises CHF_3 and argon for etching the oxide with high oxide/polysilicon selectivity.
- 15
25. The process of claim 16, wherein the material is oxide over polysilicon, comprising power of 1 kilowatt, 200 MHz applied to the antenna; relatively lower frequency bias power of about 600 watts applied to the wafer support electrode; gas chemistry comprising CHF_3 and argon; and the chamber pressure comprising 10-30 millitorr, thereby etching the oxide at a rate of about 5,000-6,000 Angstroms/minute with 20/1 oxide/poly selectivity.
- 20
26. The process of claim 16, wherein the material etched is oxide over aluminum and wherein the gas chemistry comprises $\text{CHF}_3/\text{CF}_4/\text{argon}$ for etching the oxide without sputtering the aluminum.
- 25
27. The process of claim 16, wherein the material etched is oxide over aluminum, comprising applying antenna power of 300 to 5000 watts, preferably of 300 to 2500 watts, at 50 to 80 MHz, preferably 50 to 400 MHz; bias power of 100 to 1000 watts, preferably 100 to 500 watts; gas chemistry comprising fluorine-containing gas and at least one of hydrogen- and carbon-containing gas and inert gas; and pressure less than about 500 millitorr, preferably less than about 100 millitorr.
- 30
28. The process of claim 16 or 27 wherein the material etched is oxide over aluminum, comprising applying antenna power of 800 to 2000 watts at 50-250 MHz; bias power of 100-300 watts; gas chemistry comprising one or more gases selected from CHF_3 , CF_4 , C_2F_6 , C_4F_8 , CHF_3 , CH_3F , CH_4 , hydrogen, oxygen and inert gas; and pressure within the range of about 5 millitorr to about 50 millitorr.
- 35
29. The process of claim 16, wherein the material is oxide over aluminum; power of 1.5 kilowatt, 200 MHz is applied to the antenna; relatively lower frequency bias power of about 200 watts is applied to the wafer support electrode; the gas comprises 75/75/120 sccm $\text{CHF}_3/\text{CF}_4/\text{argon}$; and the chamber pressure is 10-30 millitorr, thereby etching the oxide at a rate of about 4,000-5,000 Angstroms/minute without sputtering the aluminum.
- 40
30. The process of one of claims 13 to 16 wherein the material etched is oxide, comprising applying antenna power of 100 to 1000 watts at 50 to 800 MHz; gas chemistry comprising fluorine-containing gas; and bias power of about 0 to 200 watts.
- 45
31. The process of claim 16, wherein the material etched is oxide, comprising applying bias power of 50 to 400 MHz; gas chemistry selected from CF_4 , C_2F_6 , NF_3 and SF_6 ; and chamber pressure within the range of about 5 millitorr to 100 millitorr.
- 50
32. The process of one of claims 13 to 16, wherein the material etched is oxide, comprising applying power of about 50 to 250 MHz to the antenna and using a gas chemistry comprising at least one gas selected from CF_4 and NF_3 .
- 55
33. The process of claim 16, wherein the material is oxide; power of 200-1,000 watts at 200 MHz is applied to the antenna; the gas comprises 30-120 sccm CF_4 , and the chamber pressure is 10-50 millitorr, thereby etching the oxide at a rate of about 100 to 1,000 Angstroms/minute at a relatively low cathode sheath voltage of 10-100 volts.

** 1 Angstrom/min = 0.1 nm/min

34. The process of claim 16, wherein the material etched is oxide, comprising applying antenna power of 500 to 5000 watts, preferably 500 to 2500 watts at 50 to 800 MHz, preferably 50 to 400 MHz; bias power of 0 to 500 watts, preferably 0 to 300 watts; fluorine-containing gas chemistry; and chamber pressure less than about 50 torr^{***}, preferably in the range of 0.5 torr to 20 torr for isotropically etching the oxide.
35. The process of claim 16, wherein the material etched is oxide, comprising applying antenna power of 500 to 2500 watts at 50 to 250 MHz; bias power of 0 to 300 watts; gas chemistry comprising one or more gases selected from CF₄, C₂F₆, NF₃ and SF₆; chamber pressure within the range of about 0.5 torr to about 5 torr; and a wafer temperature of less than about 125 °C, for isotropically etching the oxide.
36. The process of claim 16, wherein the material is oxide; power of 1-1.5 kilowatt at 20 MHz is applied to the antenna; the gas comprises 500-2,000 sccm NF₃ or CF₄; the chamber pressure is about 1 torr and the wafer support cathode is maintained at about 60-75 °C, thereby isotropically etching the oxide at a rate of about 2,500-4,500 Angstroms/minute.
37. The process of claim 16, wherein the material etched is polysilicon, comprising applying antenna power of 200 to 1500 watts, preferably 300 to 1000 watts, at 50 to 800 MHz, preferably at 50 to 400 MHz; bias power of 0 to 500 watts, preferably 0 to 300 watts; halogen-containing gas chemistry; and pressure within the range of 1 millitorr to 500 millitorr, preferably of 1 millitorr to 100 millitorr.
38. The process of claim 16, wherein the material etched is polysilicon, comprising applying antenna power of 300 to 750 watts at 50 to 250 MHz; bias power of 0 to 200 watts; gas chemistry comprising at least one gas selected from chlorine, hydrogen bromide, helium, argon, oxygen and sulfur hexafluoride; and pressure within the range of about 1 millitorr to 100 millitorr.
39. The process of claim 16, wherein the material is polysilicon; power of 0.5 kilowatt, 200 MHz is applied to the antenna; relatively lower frequency power of about 500 watts is applied to the wafer support electrode; the gas comprises 80/100/(0-4) sccm Cl₂/He/O₂; and the pressure is 10-50 millitorr, thereby etching the polysilicon at a rate of about 3,000-4,000 Angstroms/minute with 35/1 poly/oxide selectivity.
40. The process of claim 13 or 16, wherein the material etched is photoresist, comprising applying antenna power of 300 to 5000 watts at 50 to 800 MHz; bias power of less than about 1000 watts; gas chemistry comprising at least one gas selected from oxygen, fluorine-containing gas, and nitrogen; and power of 100 millitorr to 50 torr.
41. The process of claim 13 or 16, wherein the material etched is photoresist, comprising applying antenna power of 300 to 2500 watts at 50 to 400 MHz; bias power of less than about 1000 watts, gas chemistry comprising at least one oxygen source gas selected from oxygen and nitrous oxide, and at least one gas selected from nitrogen, CF₄, C₂F₆, NF₃ and SF₆; and power of 500 millitorr to 10 torr.
42. The process of claim 13 or 16, wherein the material etched is photoresist, comprising applying antenna power of 300 to 2500 watts at 50 to 250 MHz; bias power of less than about 1000 watts; gas chemistry comprising 500 to 2000 sccm oxygen-containing gas selected from oxygen and nitrous oxide, and at least one gas selected from less than about 5000 sccm nitrogen, CF₄ and NF₃; and pressure of 500 millitorr to 5 torr.
43. The process of claim 13 or 16, wherein the material is photoresist; power of 1-1.5 kilowatt at 200 MHz is applied to the antenna, the gas comprises 800-1,000 sccm O₂, 0-200 sccm N₂ and 0-200 sccm CF₄; the chamber pressure is about 1 torr; and the wafer support cathode is maintained at about 100-2,000 °C, thereby etching the photoresist at a rate of about 1-3 μm/minute.
44. The process of claim 16, for etching photoresist, comprising antenna power of 300 to 2,500 watts at 50 to 800 MHz; bias power less than about 500 watts, gas chemistry comprising one or more gases or gas combinations selected from (1) oxygen and (2) oxygen and fluorine-containing gas; and chamber

*** 1 torr = 1.3 mbar

pressure within the range about 1 millitorr to about 500 millitorr, for anisotropically etching the photoresist.

- 5 45. The process of claim 16, for etching photoresist, comprising antenna power of 300 to 1,500 watts at 50 to 250 MHz; bias power less than about 300 watts; gas chemistry comprising (1) one or more oxygen-containing gases selected from oxygen and nitrous oxide and (2) one or more fluorine-containing gases selected from CF_4 , NF_3 , C_2F_6 and SF_6 , chamber pressure within the range about 1 millitorr to about 100 millitorr; and wafer temperature of less than about 125°C , for anisotropically etching the photoresist, wherein the flow rate ratio of the fluorine-containing gas to the oxygen-containing gas preferably is
10 $(0-300)/(10-300)$.
46. The process to claim 16, wherein the material is photoresist; power of 1 kilowatt at 200 MHz is applied to the antenna; relatively lower frequency power of 0-200 watts is applied to the wafer support electrode; the gas comprises 30-100 sccm O_2 and 0-50 sccm CF_4 ; the chamber pressure is 10-30
15 millitorr; and the wafer support electrode is maintained at about 60°C , thereby etching the photoresist anisotropically at a rate of about $0.8-2\mu\text{m}/\text{minute}$.
47. The process of claim 14 or 16 for low pressure plasma deposition of silicon nitride, using gas chemistry comprising silicon-containing gas and nitrogen-containing gas and a pressure of < 50 millitorr.
20
48. The process of claim 14 or 16, for low pressure plasma deposition of nitride, comprising antenna power of 300 to 5,000 watts at 50 to 800 MHz; bias power less than about 1,000 watts; gas chemistry comprising silicon-containing gas and nitrogen-containing gas; and chamber pressure less than about 500 millitorr.
25
49. The process of claim 14 or 16 for low pressure plasma deposition of silicon nitride, comprising top antenna power of 500 to 2,500 watts at 50 to 250 MHz, bottom bias power of 0-600 watts, gas chemistry of 30-300 sccm SiH_4 , 0-50 sccm NH_3 and 100-1,000 sccm N_2 ; pressure of 1-100 millitorr; and wafer temperature of about $100-500^\circ\text{C}$.
30
50. The process of claim 14 or 16 for low pressure plasma deposition of silicon oxynitride using gas chemistry, comprising silicon-containing gas, nitrogen-containing gas and oxygen-containing gas; and pressure < 50 millitorr.
- 35 51. The process of claim 16, for low pressure plasma deposition of silicon oxynitride, comprising antenna power of 500 to 2,500 watts at 50 to 250 MHz, bottom bias power of 0-600 watts, gas chemistry comprising 30-300 sccm SiH_4 , 0-50 sccm NH_3 , 100-1,000 sccm N_2 and oxygen-containing gas selected from oxygen and nitrous oxide; pressure of 10-50 millitorr; and wafer temperature of about $200-400^\circ\text{C}$.
40
52. The process of claim 16, for low pressure plasma deposition of silicon oxynitride, comprising antenna power of 500 to 2,500 watts at 50 to 250 MHz, bottom bias power of 0 to 600 watts, gas chemistry comprising 30-200 sccm SiH_4 , 0-50 sccm NH_3 , 100-1,000 sccm N_2 , and 100-1,000 sccm oxygen-containing species selected from N_2O and O_2 ; pressure of 1-100 millitorr; and wafer temperature of
45 about $100-500^\circ\text{C}$.
53. The process of claim 14, for effecting high pressure isotropic conformal deposition of silicon dioxide.
54. The process of claim 14, for high pressure isotropic conformal deposition of silicon oxide, comprising
50 antenna power of 300-5,000 watts, preferably 200 -2,500 watts, at 50 to 800 MHz, preferably at 50-250 MHz; 30-100 sccm of silicon-containing gas selected from silane and TEOS and 200-3,000 sccm of N_2O ; chamber pressure of 500 millitorr to 50 torr, preferably 1 to 10 torr, and wafer temperature of about $100-500^\circ\text{C}$.
- 55 55. The process of claim 14, for high pressure isotropic conformal deposition of silicon nitride or silicon oxynitride, comprising antenna power of 300-5,000 watts at 50 - 800 MHz gases selected from silane, ammonia, nitride and nitrous oxide and a chamber pressure of 500 millitorr to 50 torr.

56. The process of claim 55, wherein silicon nitride is preferably deposited using antenna power of 300 to 2,500 watts at 50-400 MHz; a gas mixture comprising silane, ammonia and nitrogen, and pressure of 500 millitorr to 10 torr preferably using antenna power of 500-1,500 watts at 50-250 MHz, bias power of 0-300 watts; the gas mixture comprising 30-100 sccm SiH_4 , 0-30 sccm NH_3 and 400-5,000 sccm N_2 ; and the wafer temperature being 100-500 °C and more preferably when the chamber pressure is 1-10 torr and the wafer temperature is 200-400 °C.

57. The process of claim 55, wherein silicon oxynitride is deposited using antenna power of 300-2,500 watts at 50-400 MHz; a gas mixture comprising silane, ammonia, nitrogen and nitrous oxide; and chamber pressure 500 millitorr to 10 torr, preferably using antenna power of 0.5-1.5 kW at 50-250 MHz; a bias power of 0-300 watts; a gas mixture comprising 30-100 sccm ammonia, 0-30 sccm NH_3 , 100-2,500 sccm nitrogen and 100-2,500 sccm N_2O ; the pressure being 500 millitorr to 50 torr; and the wafer temperature being 100-500 °C and more preferably when the pressure is 1-10 torr and wafer temperature is 200-400 °C.

58. The process of claim 13 or 16, for etching the material aluminum, comprising antenna power of 300 to 2,500 watts at 50 to 800 MHz; bias power of 0 to 600 watts; gas chemistry comprising one or more gases selected from chlorine-containing gas and bromine-containing gas; and chamber pressure within the range of about 1 millitorr to about 300 millitorr.

59. The process of claim 16, for etching the material aluminum, comprising antenna power of 500 to 1,500 watts at 50 to 400 MHz; bias power of 100 to 400 watts; gas chemistry comprising one or more gases selected from Cl_2 , BCl_3 and BBr_3 ; and chamber pressure within the range about 1 millitorr to about 100 millitorr.

60. The process of claim 13 or 16 for etching aluminum, comprising gas chemistry selected from one or more of chlorine-containing gas and bromine-containing gas, wherein the gas mixture preferably further comprises the additive Br_3 , boron tribromide and the process is carried out more preferably using antenna power of 600 to 800 watts at 50 to 250 MHz; bias power of 100 to 200 watts; a BCl_3/Cl_2 flow rate ratio of (30-100)/(30-100); and chamber pressure within the range about 10 millitorr to about 50 millitorr.

61. The process of claim 13 or 16, comprising etching tungsten using fluorine-containing gas chemistry, preferably by applying:

- a) antenna power of 200-500 watts at 200 MHz; gas chemistry comprising 0-200 sccm SF_6 , 0-200 sccm NF_3 and 0-200 sccm argon; and chamber pressure of 10-100 millitorr; or
- b) antenna power of 100 to 2,500 watts at 50 to 800 MHz; or
- c) antenna power of 200 to 500 watts at 50 to 250 MHz; bias power of 0 to 200 watts; gas chemistry comprising 0-200 sccm SF_6 , 0-200 sccm NF_3 , and 0-200 sccm argon; and chamber pressure within the range about 10 millitorr to about 100 millitorr.

62. The process of claim 13 or 16, comprising anisotropically etching single crystal silicon using gas chemistry selected from one or more of HBr , O_2 , He and SiF_4 , preferably by applying:

- a) antenna power of 100 to 2500 watts at 50 to 800 MHz; bias power of 0 to 500 watts; and chamber pressure within the range of about 1 millitorr to about 500 millitorr;
- b) antenna power of 300 to 700 watts at 50 to 250 MHz; bias power of 50 to 200 watts; gas chemistry comprising one or more gases selected from HBr , NF_3 , He and O_2 ; and chamber pressure within the range 10 millitorr to 50 millitorr for anisotropically etching the silicon; or
- c) antenna power of 3000-700 watts; bias power 50-150 watts to provide a cathode sheath voltage of about 100 volts; gas mixture comprising 30-100 sccm HBr , 0-20 sccm NF_3 , 0-10 sccm oxygen, 0-10 sccm helium and 0-20 sccm SiF_4 ; and pressure 10-50 millitorr.

63. The process of claim 13 or 16, wherein the material etched is selected from titanium tungsten and titanium nitride compounds.

64. The process of claim 13 or 16, wherein the material etched is a barrier layer selected from titanium tungsten and titanium nitride compounds interposed between oxide and aluminum materials wherein antenna frequency is preferably 50 to 800 MHz.

65. The process of claim 13 or 16 wherein the material etched is a barrier layer selected from titanium tungsten and titanium nitride compounds interposed between oxide and aluminum materials, and wherein the antenna power is 300 to 600 watts at 50 to 250 MHz; the bottom bias power is 100 to 200 watts; the gas comprises 10 to 100 sccm BCl_3 , 0 to 20 sccm chlorine and 1 to 20 sccm CF_4 ; and the chamber pressure is 5 to 50 millitorr.
5
66. The process of claim 15 or 16, comprising first, depositing a layer of silicon oxide over aluminum and, second, effecting sputter facet deposition by continuing the oxide deposition and simultaneously sputter etching the depositing oxide at an etch rate less than the deposition rate, preferably using antenna power of 500 to 2,500 watts at 50 to 250 MHz.
10
67. The process of Claim 66, wherein the first, deposition step comprises applying antenna power of 500 to 2,500 watts at 50 to 250 MHz with substantially no bottom bias power to provide a low cathode sheath voltage; a gas comprising a silicon-containing gas and oxygen; chamber pressure of 1 to 30 millitorr; and a wafer temperature of 300 to 400 °C; and wherein the second, facet deposition step comprises applying bottom bias power of 200 to 1000 watts to provide a cathode sheath voltage of about 200 to 600 volts; and adding 400 to 800 sccm argon for effecting net deposition with simultaneous etching.
15
68. The process of claim 67, wherein preferably the first, deposition step uses antenna power of 1 to 2 kW and a gas mixture comprising 30 to 100 sccm silane and 30 to 200 sccm oxygen and the second, facet deposition step adds 400 to 800 sccm argon and/or the ratio of sputter etch rate to deposition rate is selected to planarize the wafer topography.
20
69. The process of claim 19, wherein the gas includes a non-reactive gas for sputter etching the oxide.
25
70. An RF plasma processing system, especially for carrying out the process of one of the preceding claims, comprising: a vacuum chamber (16); means in the vacuum chamber for supporting an article such as a semiconductor wafer (5); means (22, 25) for supplying processing gas into the chamber (16); and means (25) for coupling high frequency elliptically polarized electromagnetic energy into the chamber (16) to generate a plasma within the chamber (16).
30
71. The system of claim 70 wherein the coupling means is a single turn of multiple turn substantially closed loop resonant antenna (25).
72. The system of claim 70 wherein the system includes a conductive shield (46) between the antenna (25) and the chamber (16) for preventing direct coupling of the electric field component of the high frequency electromagnetic energy into the chamber (16).
35
73. The system of one of claims 70 to 72 further comprising power supply means (26) for supplying high frequency power to the antenna (25) and control means for automatically and iteratively adjusting the frequency of the antenna to resonance and the input impedance thereof to the impedance of the power supply means.
40
74. The system of one of claims 70 to 73 wherein the physical length of the antenna (25) approximates $n\lambda/4$, where n is a small odd integer and λ is the wavelength of the electromagnetic excitation frequency.
45
75. The system of one of claims 70 to 73 wherein the physical length of the antenna (25) approximates $n\lambda/4$, where n is a small even integer and λ is the wavelength of the electromagnetic excitation frequency.
50
76. The system of one of claims 70 to 73, wherein the physical length of the antenna (25) approximates $\lambda/2$, where λ is the wavelength of the electromagnetic excitation frequency.
77. The system of one of claims 70 to 76, further comprising means (41) for applying a voltage to the wafer support means (32) to control the cathode sheath voltage.
55
78. The system of claim 77, further comprising means for automatically varying power to the wafer support

electrode for maintaining a constant D.C. bias.

79. The system of one of claims 70 to 78, further comprising means (47) for applying a static magnetic field orthogonal to the plane of the antenna (25) selected from uniform (51) diverging (52) and magnetic mirror field (53, 54) configurations for controlling the location and transport of the plasma relative to the wafer (65).
80. The system of one of claims 70 to 79, wherein the wafer support electrode includes a surface for supporting a wafer (5) thereon and further comprising means for applying a multipolar cusp field (54) in a lower chamber region (16A) for providing a relatively high intensity field region about the periphery inside the chamber walls (12) and a relatively lower intensity field region along the wafer support surface.
81. The system of claim 79 or 80, further comprising magnetic shunt means proximate the wafer support electrode for diverting the static magnetic field from the wafer support electrode to provide a relatively lower intensity field region along the wafer support surface.
82. The system of one of claims 70 to 81, further comprising a high frequency reflector (44) surrounding the antenna (25) outside the chamber (16) for preventing radiation of the high frequency energy into free space.
83. The system of one of claims 70 to 82, wherein the chamber (16) includes a generally cylindrically-shaped dielectric dome (17); wherein the coupling means is a substantially closed loop antenna (25) surrounding the dome (17); and further comprising a conductive shield (46) between the antenna (25) and the dome (17) for preventing coupling of the direct electric field component of the electromagnetic energy into the chamber, especially for generating a plasma concentrated in the plane of the ring antenna (25) within the dome (17) and extending the plasma downstream to the wafer (5) support electrode.
84. The system of claim 70, wherein the coupling means is a substantially closed loop antenna (25) surrounding the dome (17) and the wafer support electrode is located proximate to the plane of the antenna (25); and further comprising a conductive shield (46) between the antenna (25) and chamber (16) for preventing coupling of the direct electric field component of the electromagnetic energy into the chamber (16), for generating a plasma concentrated in the plane of the ring antenna and immersing the region of the wafer support electrode in the plasma.
85. The system of claim 84, further comprising means for applying a voltage to the wafer support means to control the cathode sheath voltage.
86. The system of claim 71, wherein the chamber (16) includes a dielectric window in one side thereof and the antenna (25) is mounted proximate the window external to the chamber.
87. The system of claim 71, wherein the antenna is mounted within the chamber.
88. The system of claim 71, wherein the high frequency energy is coupled to the antenna via one of inductive, capacitive and conductive impedance for matching the impedance of the antenna to the high frequency source or wherein the high frequency energy is coupled to the antenna through a variable capacitor for matching the impedance of the antenna to that of the high frequency source.
89. The system of claim 71, comprising means connected to the antenna selected from fixed and distributed, inductive and capacitive impedances, for tuning the antenna to resonance.
90. The system of claim 71, comprising a variable capacitor connected to the antenna for tuning the antenna to resonance.
91. The system of claim 71, wherein the length of the antenna approximates $\lambda/2$ and λ is the wavelength of high frequency RF energy at the plasma excitation frequency, and further comprising a variable capacitor connected near the $\lambda/4$ point on the antenna for tuning the antenna to

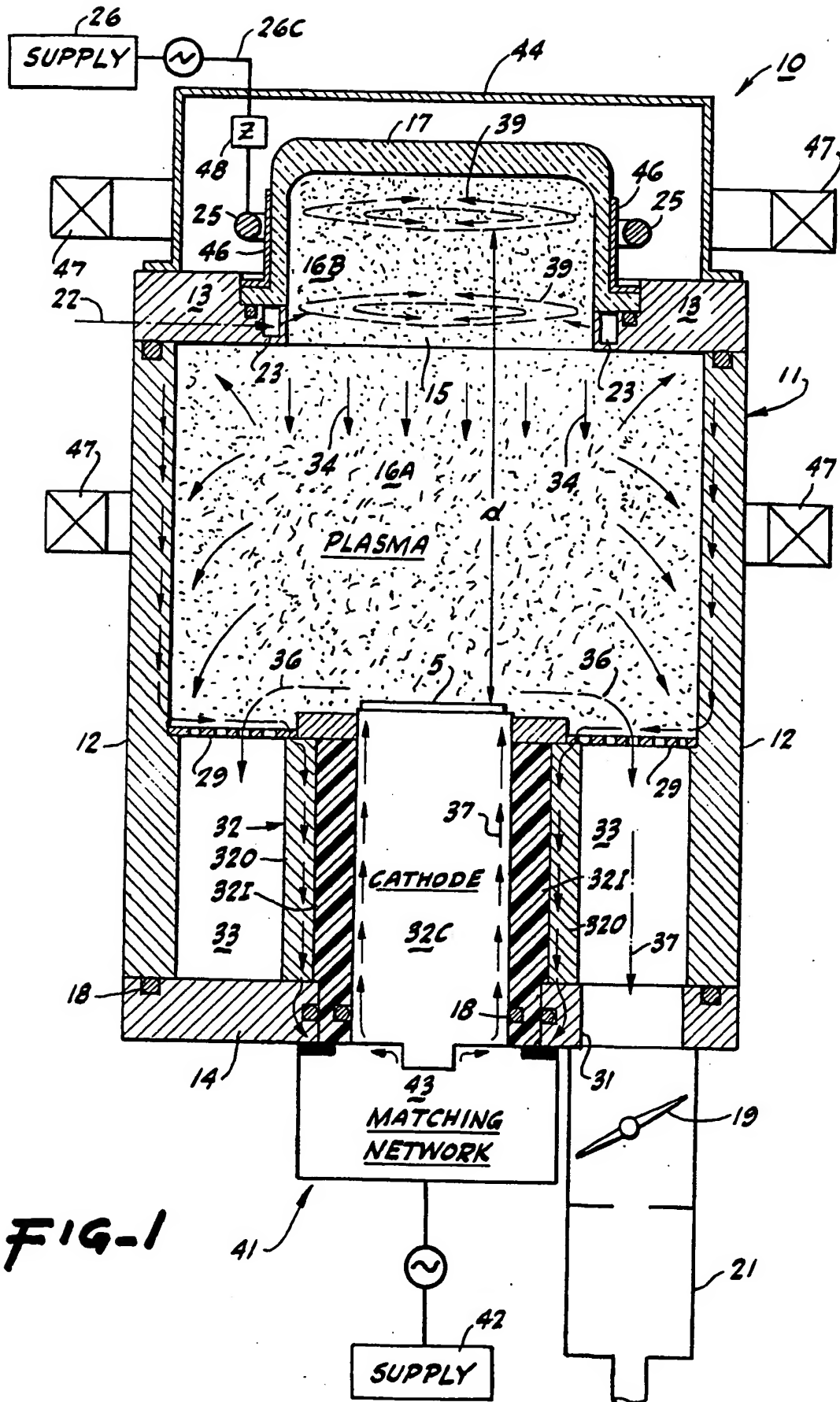
resonance.

92. The system of one of claims 70 to 91, further comprising a biased grid for extracting a stream of charged ions or electrons from the plasma.
- 5 93. The system of claim 92, further comprising a neutralization grid spaced from the extraction grid for extracting a stream of excited neutrals and free radicals.
- 10 94. The system of one of claims 70 to 93, wherein the coupling means couples circularly polarized electromagnetic energy into the chamber.
- 15 95. A plasma processing reactor, especially for carrying out the process of one of the preceding claims 1 to 69 and/or for use in the RF plasma processing system of one of claims 70 to 94, comprising: a housing (11) including a dielectric dome (17) defining a plasma chamber (16) therein; electrode means (32C) within the plasma chamber (16) for supporting a semiconductor wafer (5); a gas inlet manifold (23) in the housing for supplying reactant gas to the plasma chamber (16); vacuum pumping means (21) communicating with the plasma chamber (16) for maintaining a vacuum therein; and a high frequency energy source (26) comprising a substantially closed loop antenna (25) surrounding the dome (17) and a conductive shield (46) interposed between the antenna (25) and the dome (17) for cooperatively shunting the direct electric field component of the high frequency electromagnetic energy from the plasma chamber (16) and coupling the magnetic component of the high frequency electromagnetic energy into the plasma chamber for inducing closed loop electric fields therein.
- 20 96. The reactor of claim 95, wherein the high frequency energy source has a frequency within the range 50-800 MHz.
- 25 97. The reactor of claim 95 or 96 further comprising means for applying AC energy of selected frequency to the wafer support electrode (32C) for controlling the cathode sheath voltage.
- 30 98. The reactor of one of claims 95 to 97, further comprising an integral transmission line structure adapted to apply AC energy of selected frequency from an external source to the plasma chamber and comprising the electrode means; an outer conductor (32O) surrounding the electrode means (32C); and an insulator (32I) between the electrode means (32C) and the outer conductor (32O) such that AC energy applied to the transmission line structure is coupled along the electrode means for increasing the cathode sheath voltage.
- 35 99. The reactor of one of claims 95 to 98, wherein the power of the AC energy controls the cathode sheath voltage.
- 40 100. The reactor of one of claims 95 to 99, wherein the power of the AC energy supply is automatically varied to maintain at least one a selected cathode sheath voltage and a DC bias.

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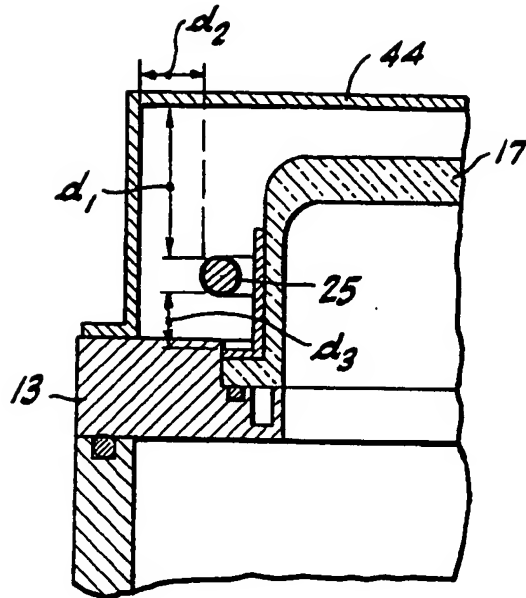


FIG-3

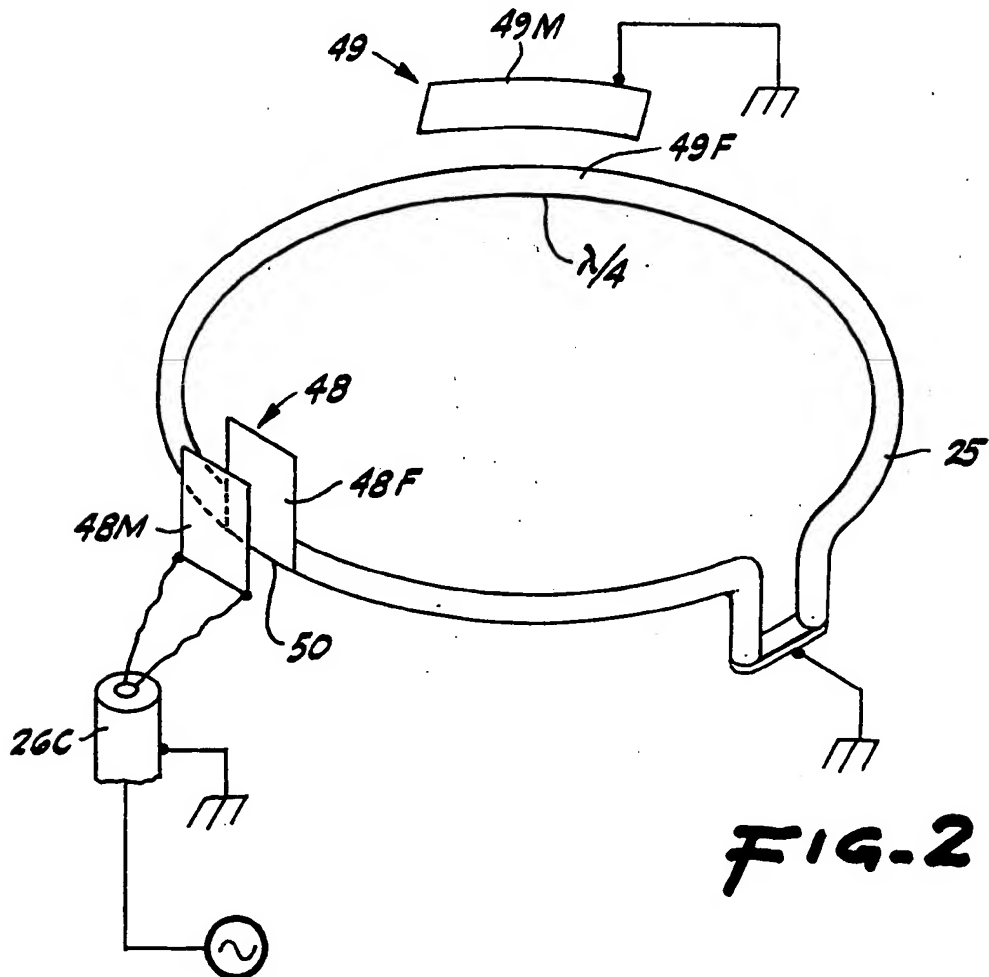


FIG-2

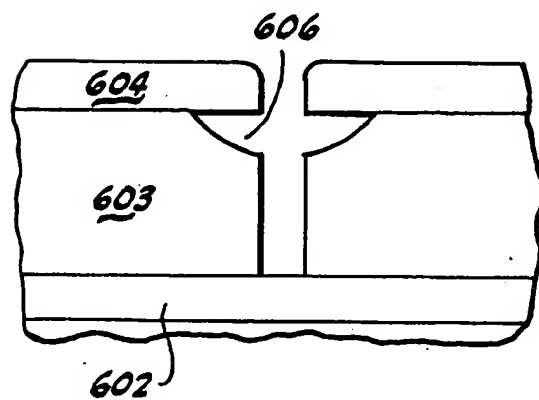
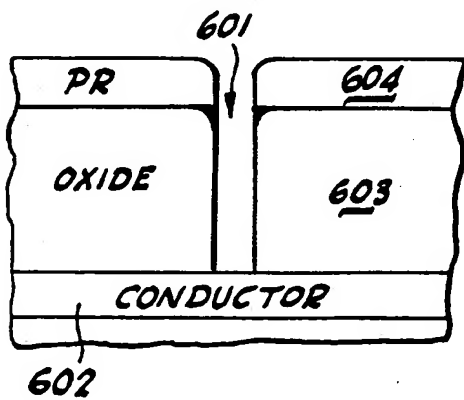
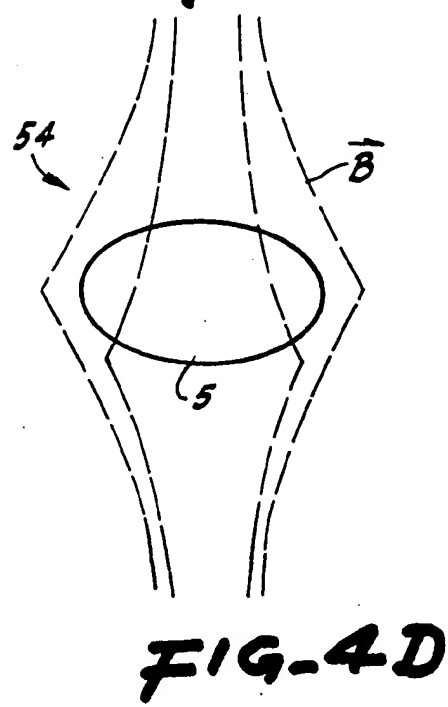
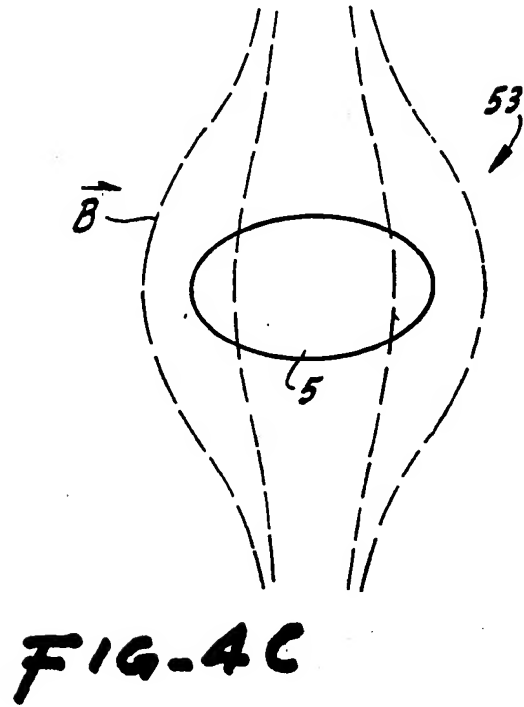
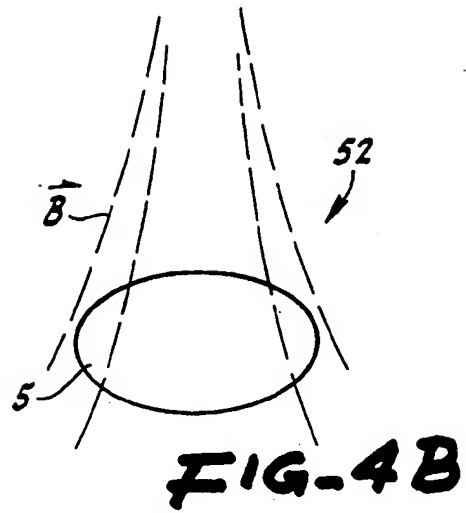
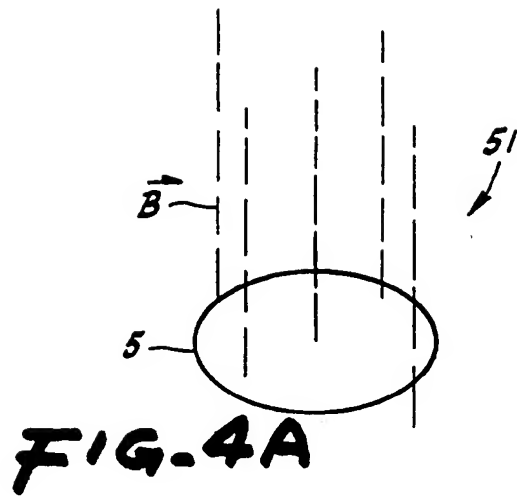


FIG-5